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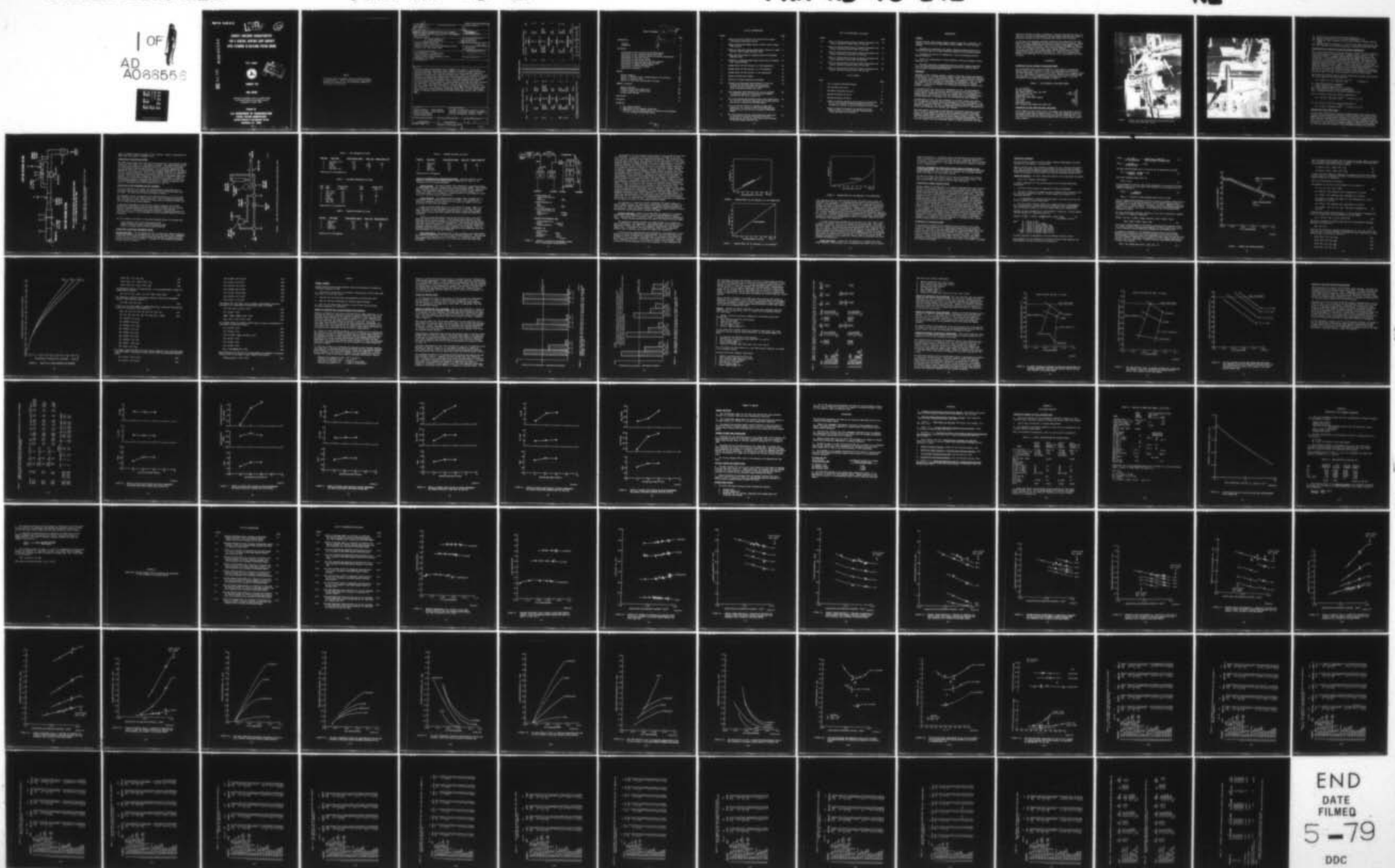

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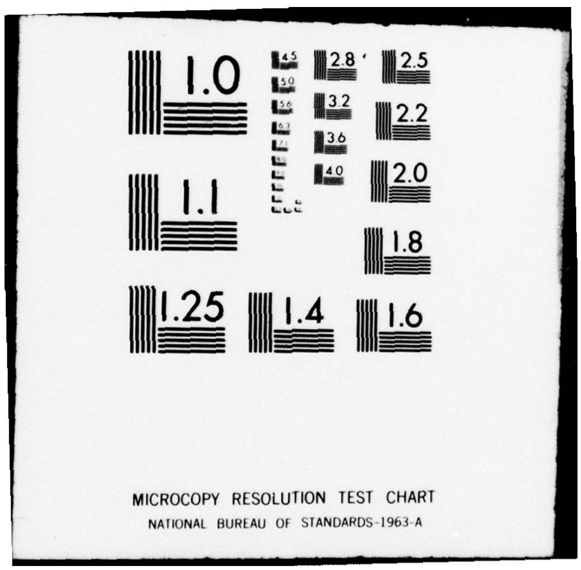
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Report No. FAA-RD-78-142

LEVEL II

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EXHAUST EMISSIONS CHARACTERISTICS FOR A GENERAL AVIATION LIGHT-AIRCRAFT AVCO LYCOMING IO-360-A1B6D PISTON ENGINE

Eric E. Becker

DEPARTMENT OF TRANSPORTATION · UNITED STATES OF AMERICA

FEBRUARY 1979

FINAL REPORT

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

Prepared for

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16. Abstract

The Avco Lycoming IO-360-A1B6D engine (S/N888-X) was tested at the National Aviation Facilities Experimental Center (NAFEC) to develop a steady state exhaust emissions data base. This data base consists of current production baseline emissions characteristics, lean-out emissions data, effects of leaning-out the fuel schedule on cylinder head temperatures, and data showing ambient effects on exhaust emissions and cylinder head temperatures. The engine operating with its current full-rich production fuel schedule could not meet the proposed Environmental Protection Agency (EPA) standard for carbon monoxide (CO) under sea level, standard-day conditions. The engine did, however, meet the proposed EPA standards for unburned hydrocarbons (HC) and oxides of nitrogen (NO_x) under the same sea level test conditions. The results of testing the engine under different ambient conditions (hot day) are also presented, and these results show a trend toward higher levels of emissions output for CO and HC while producing slightly lower levels of NO_x.

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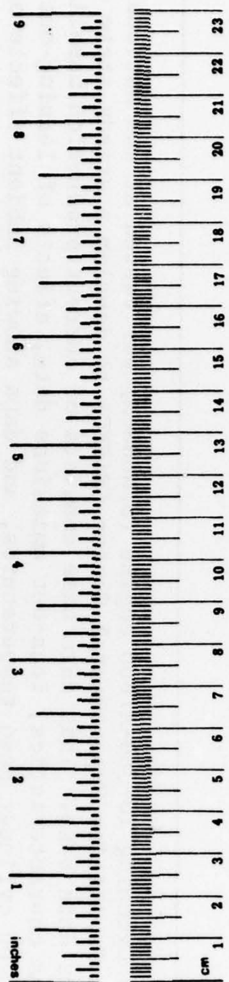
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

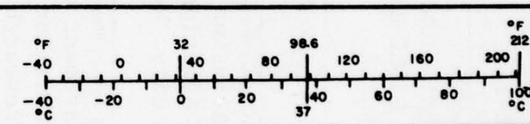
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

PURPOSE.

General aviation piston engine exhaust emission tests were conducted at the National Aviation Facility Experimental Center (NAFEC) for the following reasons:

1. Determine and establish total exhaust emissions characteristics for a representative group of current production general aviation piston engines.

2. Determine the effects of leaning-out of the fuel metering system on exhaust emissions.

3. Verify the acceptability of test procedures, testing techniques, instrumentation, etc.

4. Determine reductions in operating limits and safety margins resulting from fuel system adjustments/modifications evaluated for improved piston engine exhaust emissions characteristics.

BACKGROUND.

Beginning in 1967, Congress enacted a series of laws which added environmental considerations to the civil aviation safety, control, and promotional functions of the Federal Aviation Administration (FAA). This legislation was in response to the growing public concern over environmental degradation. Thus, the FAA was committed to the development, evaluation, and execution of programs designed to identify and minimize the undesirable environmental effects attributable to aviation.

In accordance with the Clean Air Act Amendments of 1970, the Environmental Protection Agency (EPA) established emission standards and outlined test procedures when it issued EPA rule part 87 in January 1973. The Secretary of Transportation, and therefore the FAA was charged with the responsibility for issuing regulations to implement this rule and enforcing these standards.

Implementation of this rule was contingent on the FAA's finding that safety was not impaired by whatever means was employed to achieve the standards. For this reason, the FAA undertook a program, subsequent to the issuance of the EPA emission standards in July 1973, to determine the feasibility of implementation, verify test procedures, and validate test results.

There was concern on the part of the FAA that the actions indicated as necessary in order to comply with the EPA emission standards, such as operating engines at leaner mixture settings during landing and takeoff cycles, might compromise safety and/or significantly reduce engine operating margins. Therefore, the FAA contracted with Avco Lycoming and Teledyne Continental Motors to select engines that they considered typical of their production, test these

engines as normally produced to establish a baseline emissions data base, and then alter (by lean-out adjustments) the fuel schedule and ignition timing to demonstrate methods by which the proposed EPA limits could be reached.

In the event that hazardous operating conditions were indicated by the manufacturer's tests, independent verification of data would be necessary. Therefore, it was decided that duplication of the tests be undertaken at NAFEC to provide the needed verification. This report presents the NAFEC test results for the Avco Lycoming IO-360-A1B6D piston engine (S/N888-X). It should be noted that since the time of these tests, the EPA has rescinded the promulgated piston engine standards (reference 1). This work is reported upon herein in the same light as it would have been if the requirements were still in effect.

DISCUSSION

DESCRIPTION OF AVCO LYCOMING IO-360-A1B6D ENGINE.

The IO-360-A1B6D engine tested at NAFEC is a fuel-injected, horizontally opposed engine with a nominal 360 cubic inch displacement (cid) rated at 200 brake horsepower (bhp) for a nominal brake specific fuel consumption (bsfc) of 0.50. This engine is designed to operate on 100/130 octane aviation gasoline (appendix A - Fuel Sample Analysis of NAFEC Test Fuel). The vital statistics for this engine are provided in table 1.

TABLE 1. AVCO LYCOMING IO-360-A1B6D ENGINE

No. of Cylinders	4
Cylinder Arrangement	HO
Max. Engine Takeoff Power (HP, RPM)	200, 2700
Bore and Stroke (in.)	5.125 x 4.375
Displacement (cu. in.)	361
Weight, Dry (lbs)--Basic Engine	330
Prop. Drive	Direct
Fuel Grade	100/130
Compression Ratio	8.7:1
Max. Cylinder Head Temperature Limit (°F)	475

DESCRIPTION OF TEST SETUP AND BASIC FACILITIES.

For the NAFEC sea level static tests, the engines were installed in the propeller test stand shown in figures 1 and 2. This test stand was located in the NAFEC General Aviation Piston Engine Test Facility (building 211). The test facility provided the following capabilities for testing light aircraft piston engines:

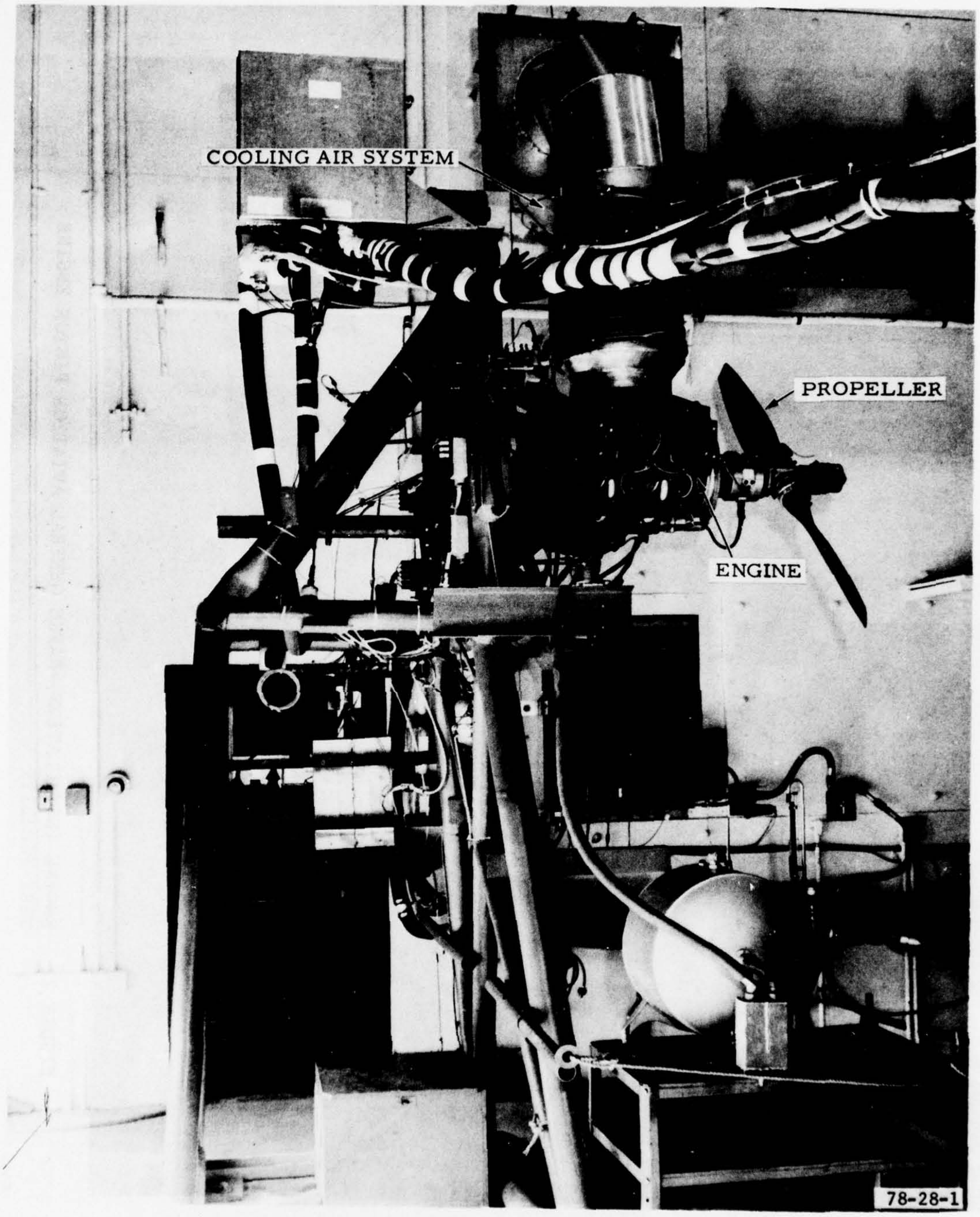


FIGURE 1. TYPICAL SEA LEVEL PROPELLER TEST STAND--PISTON ENGINE INSTALLATION--EMISSIONS TESTING

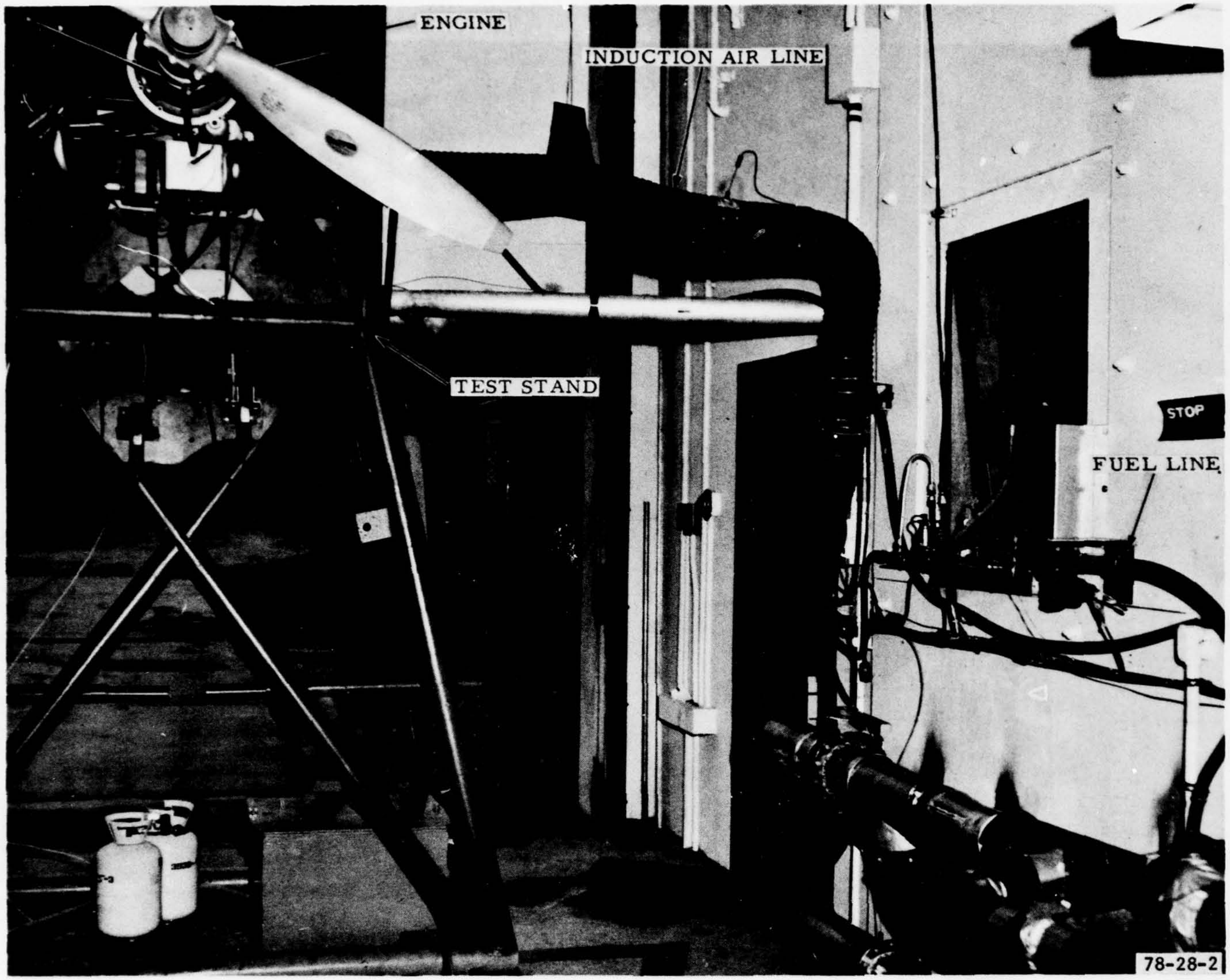


FIGURE 2. ENGINE INSTALLATION--NAFEC GENERAL AVIATION PISTON ENGINE TEST FACILITY

(1) Two basic air sources--dry bottles and ambient air
(2) Ambient temperatures (20 to 140 degrees Fahrenheit (°F))
(3) Nominal sea level pressures (29.50 to 30.50 inches of mercury absolute (inHgA)
(4) Humidity (specific humidity--0 to 0.020 lb water (H_2O) vapor/lb dry air)
(5) Fuel (100/130 octane aviation gasoline--a dedicated 5,000 gallon tank)

DESCRIPTION OF AIR INDUCTION SYSTEM AND AIRFLOW COMPUTATIONS.

The airflow system (induction system) utilized at NAFEC for testing light-aircraft piston engines is illustrated in schematic form in figure 3. This system incorporated a redundant airflow measuring system for accuracy and reliability. In the high-flow measuring section, NAFEC utilized a 3.0 inch orifice and an Autronics air meter (model No. 100-750S). The capability of this high-flow system ranged from 400 to 2000 pounds per hour (lb/h) with an estimated reading tolerance in flow accuracy of ± 2 percent. The low-flow measuring section utilized a small 1.0 inch orifice and an Autronics air meter (model No. 100-100S). The capability of this system ranged from 40 to 400 lb/h with an estimated reading tolerance in flow accuracy of ± 3 percent. The size of the basic air duct was 8.0 inches (inside diameter) for the high-flow system and 2.0 inches (inside diameter) for the low-flow system.

The airflow was computed from the orifice differential pressure and induction air density using the following equation:

$$Wa = (1891)\ (C_f)\ (d_o)^2 \left[(.03609)\ \Delta P_\rho\right]^{1/2} \qquad \text{(reference 2)}$$

ΔP = inH_2O (differential air pressure)
ρ = lb/ft^3 (induction air density)
d_o = inches (inside diameter (i.d.) of orifice)
C_f = flow coefficient for orifice (nondimensional)
1891 = conversion constant for airflow in pounds per hour.

For the 3.0-inch orifice this equation simplifies to:

$$Wa = (10{,}381.6) \left[(.03609)\ \Delta P_\rho\right]^{1/2} = 1972.23\ (\Delta\ P_\rho\ )^{1/2}$$

For the 1.0-inch orifice this equation simplifies to:

$$Wa = (1{,}189.4) \left[(.03609)\ \Delta P_\rho\right]^{1/2} = 225.955\ (\Delta\ P_\rho\ )^{1/2}$$

DESCRIPTION OF FUEL FLOW SYSTEM.

The fuel flow system utilizied during the NAFEC light-aircraft piston engine emission tests incorporated rotameters, turboflow meters, and a burette. The high-flow section incorporated a rotameter in series with a high-flow turbometer while the low-flow section incorporated a low-flow turbometer in series with a burette. The high-flow system was capable of measuring fuel flows from 50 lb/h up to 300 lb/h with an estimated reading tolerance of ± 1.0 percent. The low-flow system was capable of flow measurements ranging from 0-50 lb/h

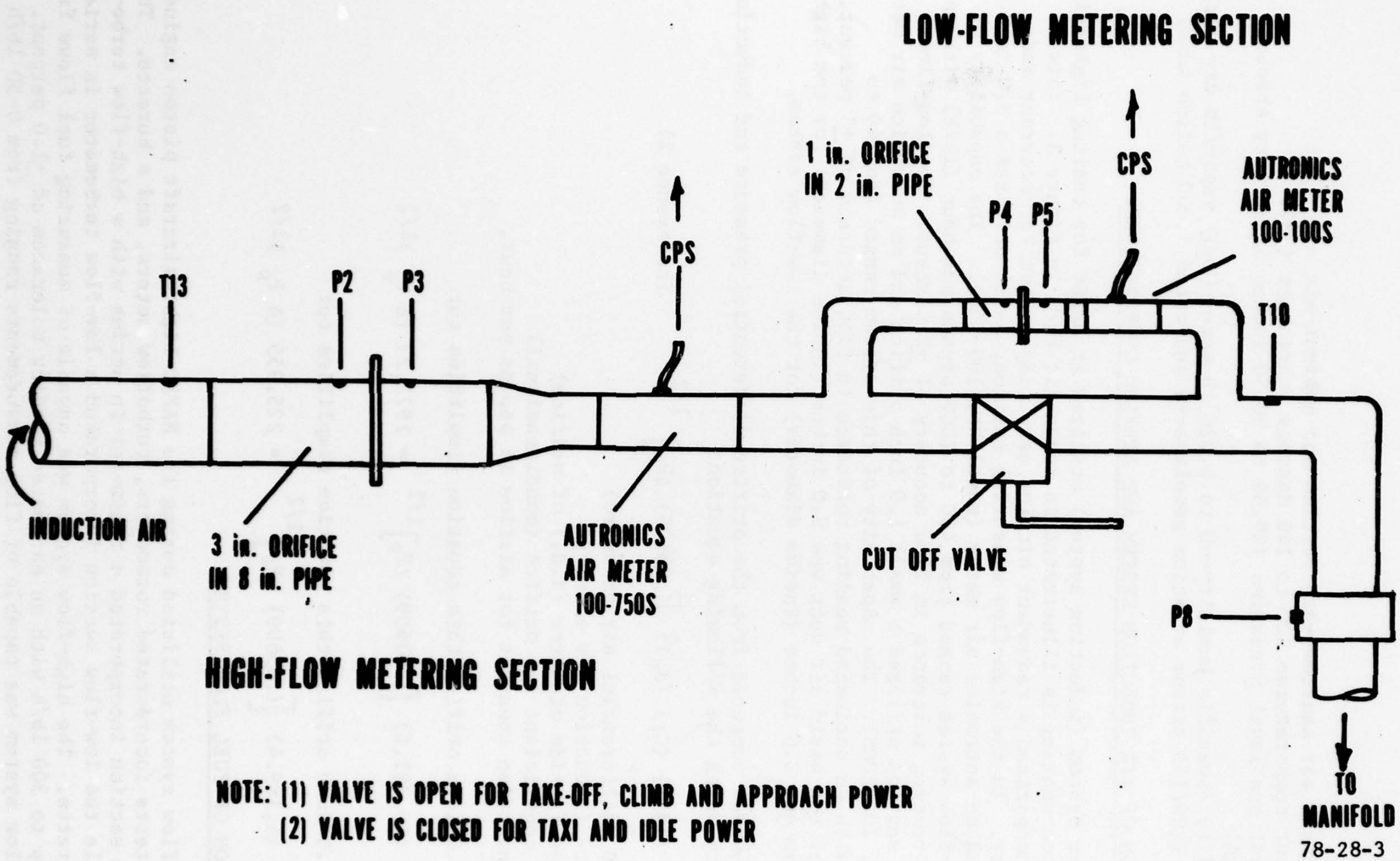


FIGURE 3. NAFEC AIR INDUCTION (AIRFLOW MEASUREMENT) SYSTEM FOR LIGHT-AIRCRAFT PISTON ENGINE EMISSION TESTS

with an estimated reading tolerance of ± 2.0 percent. Figure 4 illustrates the NAFEC fuel flow system in schematic form.

DESCRIPTION OF COOLING AIR SYSTEM.

The NAFEC piston engine test facility also incorporated a system which provided cooling air (see figure 1) to the engine cylinders. The engine mounted in the test stand was enclosed in a simulated nacelle and cooling air was provided to this enclosure from an external source. The cooling air temperature was maintained within $\pm 10^{\circ}$ F of the induction air supply temperature for any specified set of test conditions. This not only minimized variations in temperature but also minimized variations in the specific weight of air for all test conditions. All of the basic cooling air tests with the IO-360-A1B6D engine were conducted with differential cooling air pressures of 3.0 inH_2O. A range of differential cooling air pressures from 1.0 to 6.0 inH_2O were evaluated using the IO-360-B1BD engine to determine the effects of variable cooling air conditions on maximum cylinder head temperatures (see page 29).

DESCRIPTION OF TEST PROCEDURES AND EPA STANDARDS.

The data presented in this report were measured while conducting tests in accordance with specific landing and takeoff cycles (LTO) and by modal lean-out tests. The basic EPA LTO cycle is defined in table 2.

The FAA/NAFEC contract and inhouse test programs utilized an LTO cycle which was a modification of the table 2 test cycle. Table 3 defines this modified LTO cycle which was used to evaluate the total full-rich emission characteristics of light-aircraft piston engines.

An additional assessment of the test data clearly indicates that further evaluations of the general aviation piston exhaust emission must be analyzed with the climb mode emissions at 100- and 75-percent power settings (tables 4 and 5). This would then provide basis for a complete evaluation of test data and permit a total assessment of the EPA standard based on LTO cyclic tolerances.

The EPA Standards (reference 1) that were evaluated during this program were:

Carbon monoxide (CO)--0.042 lb/cycle/rated BHP
Unburned hydrocarbon (HC)--0.0019 lb/cycle/rated BHP
Oxides of nitrogen (NO_x)--0.0015 lb/cycle/rated BHP

DESCRIPTION OF EMISSIONS MEASURMENT SYSTEM.

EMISSION ANALYZERS. The instrumentation used to monitor the exhaust emissions from general aviation piston engines was basically the same as that recommended by EPA, but with a number of modifications and additions to enhance the reliability and accuracy of the system. A schematic of the emissions measurement system is shown in figure 5.

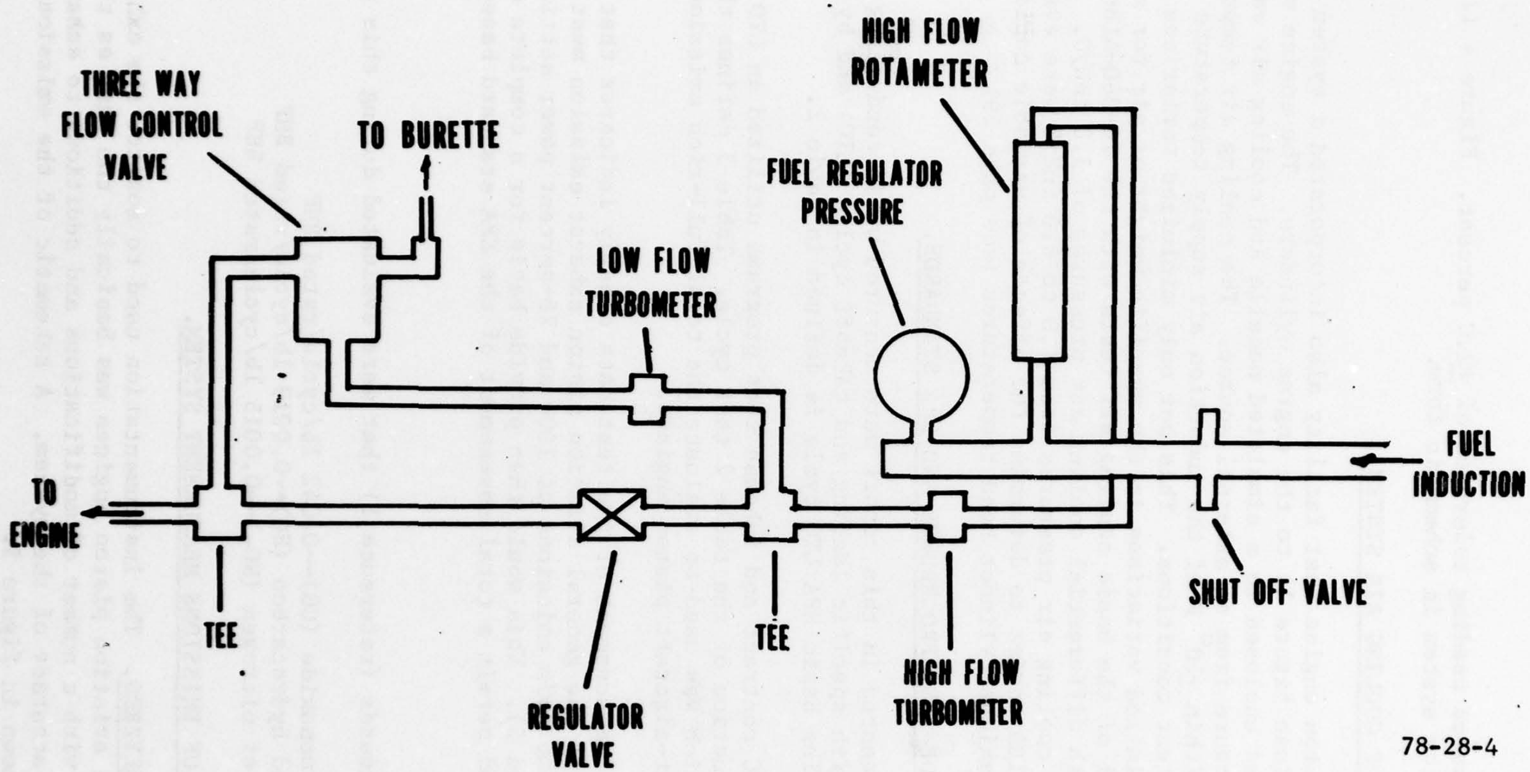


FIGURE 4. NAFEC FUEL FLOW SYSTEM FOR LIGHT-AIRCRAFT PISTON ENGINE EMISSION TESTS

TABLE 2. EPA FIVE-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min.)	Power (%)	Engine Speed (%)
1	Taxi/idle (out)	12.0	*	*
2	Takeoff	0.3	100	100
3	Climb	5.0	75-100	*
4	Approach	6.0	40	*
5	Taxi/idle (in)	4.0	*	*

*Manufacturer's Recommendation

TABLE 3. FAA/NAFEC SEVEN-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min.)	Power (%)	Engine Speed (%)
1	Idle (out)	1.0	*	*
2	Taxi (out)	11.0	*	*
3	Takeoff	0.3	100	100
4	Climb	5.0	80	*
5	Approach	6.0	40	*
6	Taxi (in)	3.0	*	*
7	Idle (in)	1.0	*	*

*Manufacturer's Recommendation

TABLE 4. MAXIMUM FIVE-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min.)	Power (%)	Engine Speed (%)
1	Taxi (out)	12.0	*	*
2	Takeoff	0.3	100	100
3	Climb	5.0	100	100
4	Approach	6.0	40	*
5	Taxi (in)	4.0	*	*

*Manufacturer's Recommended

TABLE 5. MINIMUM FIVE-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min)	Power (%)	Engine Speed (%)
1	Taxi (out)	12.0	*	*
2	Takeoff	0.3	100	100
3	Climb	5.0	75	*
4	Approach	6.0	40	*
5	Taxi (in)	4.0	*	*

*Manufacturer's Recommended

EMISSION INSTRUMENTATION ACCURACY/MODIFICATIONS. The basic analysis instrumentation utilized for this system, which is summarized in figure 5, is explained in the following paragraphs.

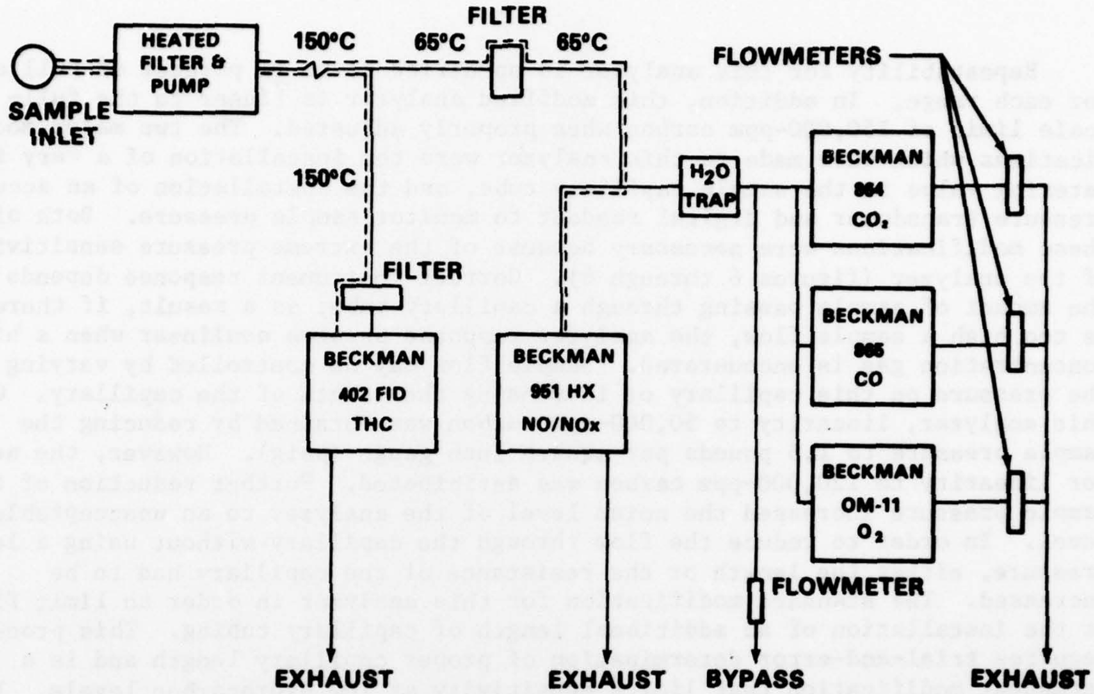
Carbon Dioxide. The carbon dioxide $(CO)_2$ subsystem is constructed around a Beckman model 864-23-2-4 nondispersive infrared analyzer (NDIR). This analyzer has a specified repeatability of ±1 percent of full scale for each operating range. The calibration ranges on this particular unit are: Range 1, 0 to 20 percent; Range 3, 0 to 5 percent. Stated accuracy for each range is, therefore, ±0.2 and ±0.05 percent respectively.

Carbon Monoxide. The subsystem used to measure carbon monoxide (CO) is constructed around a Beckman model 865-X-4-4-4 NIDR. This analyzer has a specified repeatability of ±1 percent of full scale for ranges 1 and 2 and ±2 percent of full scale for range 3.

Range 1 has been calibrated for 0 to 20 percent by volume, range 2 for 0 to 1,000 parts per million (ppm) and range 3 for 0 to 100 ppm. The wide range capability of this analyzer is made possible by using stacked sample cells which in effect give this analyzer six usable ranges when completely calibrated.

Effects of interfering gases, such as CO_2 and water vapor, were determined and reported by the factory. Interferences from 10-percent CO_2 were determined to be 12-ppm equivalent CO, and interferences from 4-percent water vapor were determined to be 6-ppm CO equivalent. Even though the interference from water vapor is negligible, a condenser is used in the CO/CO_2 subsystem to eliminate condensed water in the lines, analyzers, and flowmeters. This condensation would have decreased analyzer sensitivity and necessitated more frequent maintenance if it had been eliminated.

Total Hydrocarbons. The system that is used to measure total hydrocarbons is a modified Beckman model 402 heated flame ionization detector. This analyzer has a full-scale sensitivity that is adjustable to 150,000-ppm carbon with intermediate range multipliers 0.5, 0.1, 0.05, 0.01, 0.005, and 0.001 times full scale.



- **CARBON DIOXIDE – CO_2**
  - NONDISPERSIVE INFRARED (NDIR)
  - RANGE 0-20%
  - REPEATABILITY ± 0.2% CO_2
- **CARBON MONOXIDE – CO**
  - NDIR
  - RANGE 0-20%
  - REPEATABILITY ± 0.2% CO
- **TOTAL HYDROCARBONS – THC**
  - FLAME IONIZATION DETECTOR (FID)
  - RANGE 0-150,000 ppm_c
  - MINIMUM SENSITIVITY 1.5 ppm_c
  - LINEAR TO 150,000 ppm_c
- **OXIDES OF NITROGEN – NO_X**
  - CHEMILUMINESCENT (CL)
  - RANGE 0-10,000 ppm
  - MINIMUM SENSITIVITY 0.1 ppm
- **OXYGEN – O_2**
  - POLARAGRAPHIC
  - RANGE 0-100%
  - REPEATABILITY 0.1% O_2
  - RESPONSE 200 ms

78-28-5

FIGURE 5. SCHEMATIC OF EMISSIONS MEASUREMENT SYSTEM AND ITS MEASUREMENT CHARACTERISTICS

Repeatability for this analyzer is specified to be ± 1 percent of full scale for each range. In addition, this modified analyzer is linear to the full-scale limit of 150,000-ppm carbon when properly adjusted. The two major modifications which were made to this analyzer were the installation of a very fine metering value in the sample capillary tube, and the installation of an accurate pressure transducer and digital readout to monitor sample pressure. Both of these modifications were necessary because of the extreme pressure sensitivity of the analyzer (figures 6 through 8). Correct instrument response depends on the amount of sample passing through a capillary tube; as a result, if there is too high a sample flow, the analyzer response becomes nonlinear when a high concentration gas is encountered. Sample flow may be controlled by varying the pressure on this capillary or increasing the length of the capillary. On this analyzer, linearity to 50,000-ppm carbon was obtained by reducing the sample pressure to 1.5 pounds per square inch gauge (psig). However, the need for linearity to 120,000-ppm carbon was anticipated. Further reduction of the sample pressure increased the noise level of the analyzer to an unacceptable level. In order to reduce the flow through the capillary without using a lower pressure, either the length or the resistance of the capillary had to be increased. The standard modification for this analyzer in order to limit flow is the installation of an additional length of capillary tubing. This procedure requires trial-and-error determination of proper capillary length and is a permanent modification that limits sensitivity at low hydrocarbon levels. By installing a metering valve in the capillary, flow could be selectively set at either low flow for linearity at high concentrations or high flow for greater sensitivity at low concentrations. Installation time was reduced by eliminating the cut-and-try procedure for determining capillary length.

The addition of a sensitive pressure transducer and digital readout to monitor sample pressure was needed since the pressure regulator and gauge supplied with the analyzer would not maintain the pressure setting accurately at low pressures. Using the digital pressure readout, the sample pressure could be monitored and easily maintained to within 0.05 inH_2O.

<u>Oxides of Nitrogen</u>. Oxides of nitrogen (NO_x) are measured by a modified Beckman model 951H atmospheric pressure, heated, chemiluminescent analyzer (CL). This analyzer has a full-scale range of 10,000 ppm with six intermediate ranges. Nominal minimum sensitivity is 0.1 ppm on the 10-ppm full-scale range.

The atmospheric pressure analyzer was chosen because of its simplicity, ease of maintenance, and compactness. Anticipated water vapor problems in the atmospheric pressure unit were to be handled by the heating of the internal sample train. Interference from CO_2 quenching, common in the atmospheric pressure type CL analyzer, was checked and found to be nonexistent.

A series of major modifications were performed by the manufacturer on this analyzer to insure compliance with specifications. One such modification was installed in order to maintain the temperature of the sample stream above the dew point of the sample gas. Originally, this analyzer was specified to maintain a temperature of 140° F at all points in contact with the sample. After a survey of the 951H analyzers in use on FAA projects, it was determined that

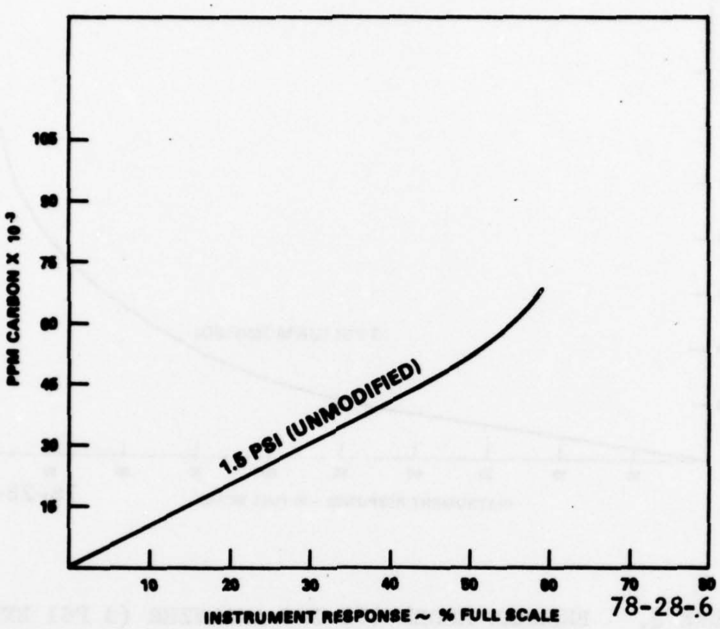


FIGURE 6. BECKMAN MODEL 402 THC ANALYZER (1.5 PSI UNMODIFIED)

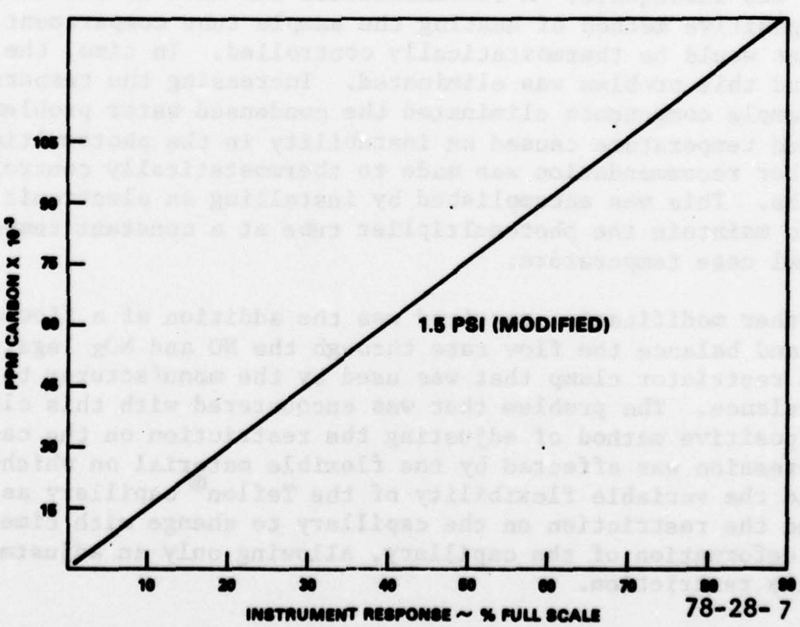


FIGURE 7. BECKMAN MODEL 402 THC ANALYZER (1.5 PSI MODIFIED)

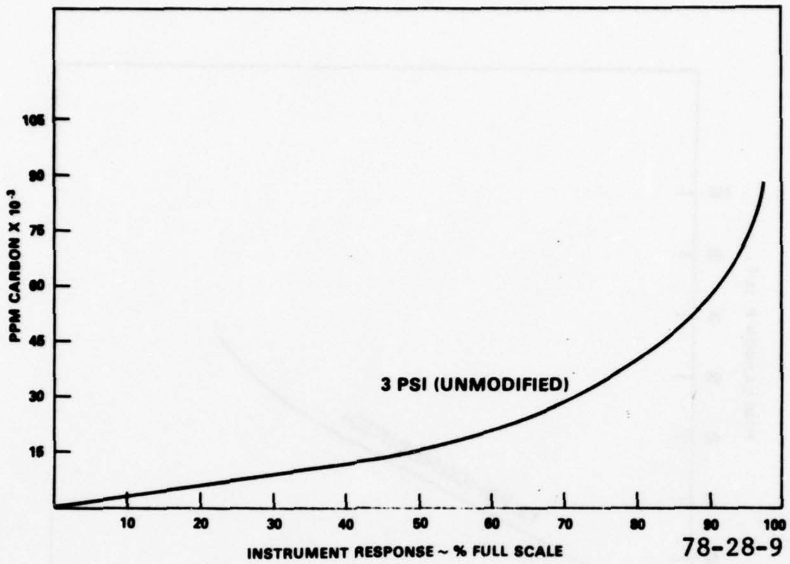


FIGURE 8. BECKMAN MODEL 402 THC ANALYZER (3 PSI UNMODIFIED)

this temperature was not being achieved because the method used to heat the components was inadequate. A recommendation was made to the manufacturer to install a positive method of heating the sample tube compartment and reaction chamber that would be thermostatically controlled. In time, the modification was made and this problem was eliminated. Increasing the temperature of the internal sample components eliminated the condensed water problem; however, the elevated temperature caused an instability in the photomultiplier tube output. Another recommendation was made to thermostatically control the temperature of this tube. This was accomplished by installing an electronic cooling jacket designed to maintain the photomultiplier tube at a constant temperature below the internal case temperature.

A further modification required was the addition of a flow control value to adjust and balance the flow rate through the NO and NO_x legs. This value replaced a restrictor clamp that was used by the manufacturer to set the NO to NO_x flow balance. The problem that was encountered with this clamp was that it was not a positive method of adjusting the restriction on the capillary. The clamp compression was affected by the flexible material on which the clamp was mounted and the variable flexibility of the Teflon® capillary as it was heated. This caused the restriction on the capillary to change with time and caused permanent deformation of the capillary, allowing only an adjustment that would increase the restriction.

<u>Oxygen Measurement</u>. Oxygen (O_2) was measured by a Beckman model OM-11 oxygen analyzer. This analyzer uses a polagraphic-type sensor unit to measure

oxygen concentration. An advanced sensor and amplification system combine to give an extremely fast response and high accuracy. Specified response for 90 percent of final reading is less than 200 milliseconds (ms) with an accuracy of less than $\pm$0.1-percent O_2. The range of this unit is a fixed 0 to 100 percent O_2 concentration.

EMISSIONS INSTRUMENTATION MODIFICATION STATUS DURING THE TESTING OF THE IO-360-A1B6D ENGINE. The tests conducted with the Avco Lycoming IO-360-A1B6D engine utilized the model 742 oxygen (O_2) analyzer and a prototype Beckman model 951H oxides of nitrogen (NO_x) analyzer.

The mode 742 oxygen (O_2) analyzer did not have the extremely fast response rate of the Beckman model OM-11 analyzer, and it was not as accurate. The data recorded with this analyzer reflects these deficiences.

DESCRIPTION OF SAMPLE HANDLING SYSTEM.

Exhaust samples are transported to the analysis instrumentation under pressure through a 35-foot-long, 3/8-inch o.d., heated, stainless steel sample line. The gas is first filtered and then pumped through this line by a heated Metal Bellows model MB-158 high temperature stainless steel sample pump. The pump, filter, and line are maintained at a temperature of 300° $\pm$4° F to prevent condensation of water vapor and hydrocarbons. At the instrument console, the sample is split to feed the hydrocarbon, oxides of nitrogen, and $CO/CO_2/O_2$ subsystems which require different temperature conditioning. The sample gas to the total hydrocarbon subsystem is maintained at 300° F while the temperature of remaining sample gas to the NO_x and $CO/CO_2/O_2$ system is allowed to drop to 150° F. Gas routed to the oxides of nitrogen subsystem is then maintained at 150° F, while the gas to the $CO/CO_2/O_2$ subsystem is passed through a 32° F condenser to remove any water vapor present in the sample. Flow rates to each analyzer are controlled by a fine-metering value and are maintained at predetermined values to minimize sample transport and system response time. Flow is monitored at the exhaust of each analyzer by three 15-centimeter (cm) rotameters. Two bypasses are incorporated into the system to keep sample transport time through the lines and condenser to a minimum without causing adverse pressure effects in the analyzers.

DESCRIPTION OF FILTRATION SYSTEM.

Particulates are removed from the sample at three locations in the system thereby minimizing downtime due to contaminated sample lines and analyzers (figure 5). Upstream of the main sample pump is a heated clamshell-type stainless steel filter body fitted with a Whatman GF/C glass fibre paper filter element capable of retaining particles in the 0.1-micron range. A similar filter is located in the total hydrocarbon analyzer upstream of the sample capillary. A Mine Safety Appliances (MSA) type H Ultra Filter capable of retaining 0.3-micron particles is located at the inlet to the oxides of nitrogen and $CO/CO_2/O_2$ subsystems.

COMPUTATION PROCEDURES.

The calculations required to convert exhaust emission measurements into mass emissions are the subject of this section.

Exhaust emission tests were designed to measure CO_2, CO, unburned hydrocarbons (HC), NO_x, and exhaust excess O_2 concentrations in percent or ppm by volume. Mass emissions were determined through calculations utilizing the data obtained during the simulation of the aircraft LTO cycle and from modal lean-out data.

COMBUSTION EQUATION. The basic combustion equation can be expressed very simply:

Fuel + Air = Exhaust Constituents

An initial examination of the problem requires the following simplifying assumptions:

1. The fuel consists solely of compounds of carbon and hydrogen.

2. The air is a mixture of oxygen and inert nitrogen in the volumetric ratio of 3.764 parts apparent nitrogen to 1.0-part oxygen (see appendix B for additional details).

3. If a stoichiometric combustion process exists, the fuel and air are supplied in chemically correct proportions.

4. The fuel (which consists usually of a complex mixture of hydrocarbons) can be represented by a single hydrocarbon having the same carbon-hydrogen ratio and molecular weight as the fuel; usually C_8H_{17} as an average fuel.

Applying the above assumptions for stoichiometric conditions, a useful general reaction equation for hydrocarbon fuel is:

$$M_fC_8H_{17} + M_a\left[O_2 + 3.764N_2 + M_wH_2O\right] \rightarrow M_1CO_2 + M_3H_2O + M_5N_2 \qquad (1)$$

(references 3 and 4)

Where
M_f = Moles of Fuel
M_a = Moles of Air or Oxygen
M_1 = Moles of Carbon Dioxide (CO_2)
M_3 = Moles of Condensed Water (H_2O)
M_5 = Moles of Nitrogen (N_2)--Exhaust
$3.764M_a$ = Moles of Nitrogen (N_2)--In Air
M_aM_w = Moles of Humidity (H_2O)--In Air

The above equation is applicable to dry air when M_w is equal to zero.

From equation (1), and assuming dry air with one mole of fuel (M_f=1.0), the stoichiometric fuel-air ratio may be expressed as:

$$(F/A)_s = \frac{\text{Wt. Fuel}}{\text{Wt. Air Required}} = \frac{12.011\ (8) + 1.008\ (17)}{12.25\ [32.000 + 3.764(28.161)]} \quad (2)$$

$$(F/A)_s = \frac{113.224}{12.25(137.998)} = 0.067$$

The mass carbon-hydrogen ratio of the fuel may be expressed as follows:

$$C/H = \frac{12.011(8)}{1.008(17)} = \frac{96.088}{17.136} = 5.607 \quad (3)$$

The atomic hydrogen-carbon ratio is:

$$17/8 = 2.125 \quad (4)$$

The stoichiometric fuel-air ratio may be expressed as a function of the mass hydrogen-carbon ratio of the fuel. The derivation of this equation is presented in reference 3.

$$(F/A)_s = \frac{C/H + 1}{11.5(C/H+3)} \quad (5)$$

$(F/A)_s$ = 0.067 for a mass hydrogen-carbon ratio of 5.607

With rich (excess fuel) mixtures, which are typical for general aviation piston engines, some of the chemical energy will not be liberated because there is not enough air to permit complete oxidation of the fuel. Combustion under such conditions is an involved process. By making certain simplifying assumptions based on test results, the effect of rich mixtures may be calculated with reasonable accuracy.

For rich (excess fuel) mixtures, equation (1) will now be rewritten to express the effects of incomplete combustion:

$$M_fC_8H_{17} + M_a\ (O_2 + 3.764N_2 + M_wH_2O) \rightarrow M_1CO_2 + M_2CO + M_3H_2O + M_4H_2 +$$
$$M_5N_2 + M_6NO + M_7CH_4 + M_8O_2 + M_9C \quad (6)$$

Since only a limited number of the exhaust constituents were measured during the testing of general aviation piston engines, the above equation can only be solved by applying certain expeditious assumptions and imperical data.

An important requirement of the FAA/NAFEC General Aviation Piston Engine Emissions Test Program was the accurate measurement of air and fuel flows. These parameters provide the data for determining engine mass flow (W_m) and with the aid of figure 9 (developed from reference 5) it is a simple computation to calculate the total moles (M_{tp}) of exhaust products being expelled by general aviation piston engines.

$$(M_{tp}) = W_m\ (\text{engine mass flow}) \div (\text{exh. mol. wt}) \quad (7)$$

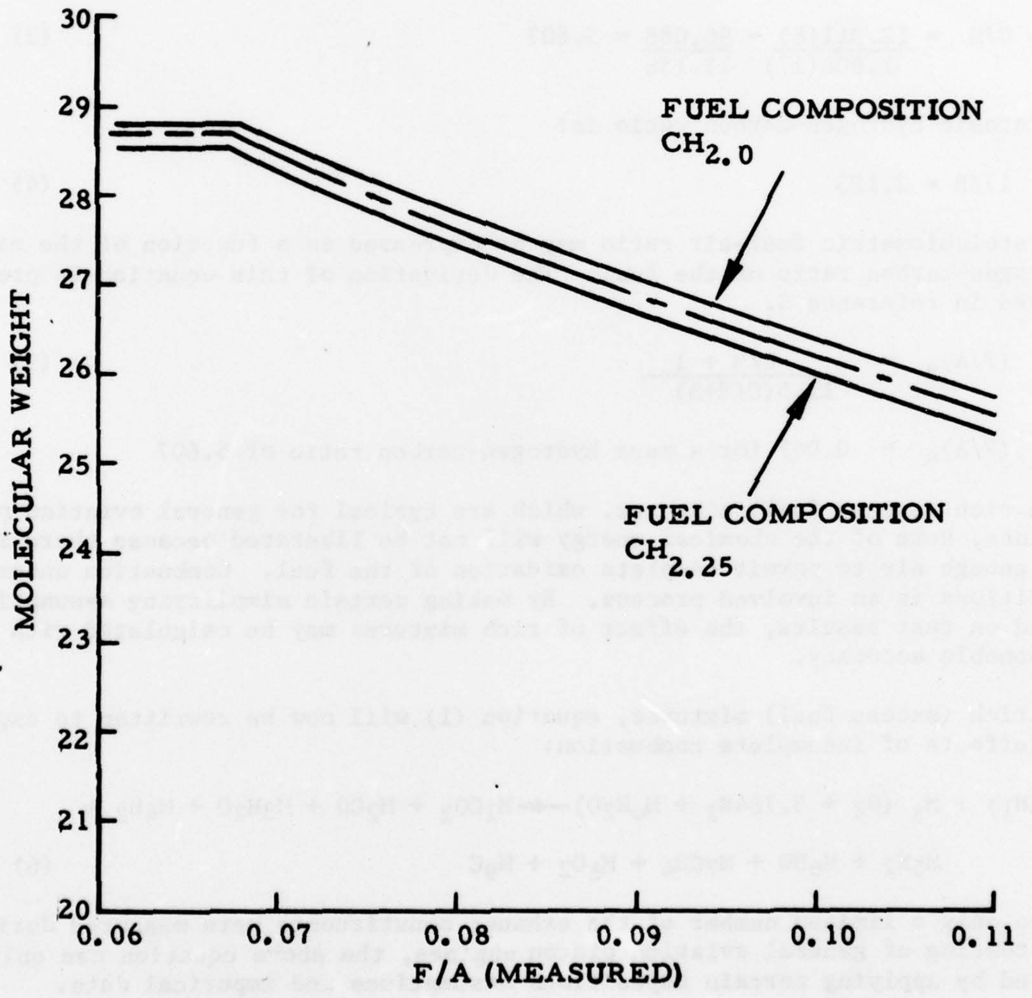


FIGURE 9. EXHAUST GAS MOLECULAR WEIGHTS

Since the unburned hydrocarbons (HC) and oxides of nitrogen (NO_x) are measured wet, it becomes a very simple matter to compute the moles of HC and NO_x that are produced by light-aircraft piston engines.

$$M_7 \text{ (Moles of HC)} = (\text{ppm} \div 10^6) \times M_{tp} \quad (8)$$

$$M_6 \text{ (Moles of } NO_x) = (\text{ppm} \div 10^6) \times M_{tp} \quad (9)$$

If the dry products (M_{dp}) of combustion are separated from the total exhaust products (M_{tp}) it is possible to develop a partial solution for five of the products specified in equation 6.

This can be accomplished as follows:

The summation of the mole fractions $(MF)_d$ for dry products is

$$m_1 + m_2 + m_4 + m_5 + m_8 = 1.0000 \quad (10)$$

$m_1 = MF(CO_2) = \%CO_2$ (measured dry), expressed as a fraction

$m_2 = MF(CO) = \%CO$ (measured dry), expressed as a fraction

$m_4 = MF(H_2) = K_4\ (\%CO)$ (see figure 10, also references 4,5, and 6), expressed as a fraction

$m_8 = MF(O_2) = \%O_2$ (measured dry), expressed as a fraction

$m_5 = 1.0000 - (m_1 + m_2 + m_4 + m_8) = \%N_2$ (dry), expressed as a fraction (11)

Utilizing the nitrogen balance equation, it is now possible to determine the moles of nitrogen that are being exhausted from the engine.

$$M_5 = 3.764\ M_a - (M_6 \div 2);\ M_6 = \text{moles (NO)} \quad (12)$$

The moles of exhaust dry products (M_{dp}) may now be determined by dividing equation 12 by equation 11.

$$M_{dp} = M_5 \div m_5 \quad (13)$$

Using all the information available from equations (7), (8), (9), (10), (11), (12), and (13), it is now possible to determine the molar quantities for seven exhaust products specified in equation 6.

$$\text{Moles } (CO_2) = M_1 = m_1 \times M_{dp} \quad (14)$$

$$\text{Moles } (CO) = M_2 = m_2 \times M_{dp} \quad (15)$$

$$\text{Moles } (H_2) = M_4 = m_4 \times M_{dp} \quad (16)$$

$$\text{Moles } (N_2) = M_5 = m_5 \times M_{dp} \quad (17)$$

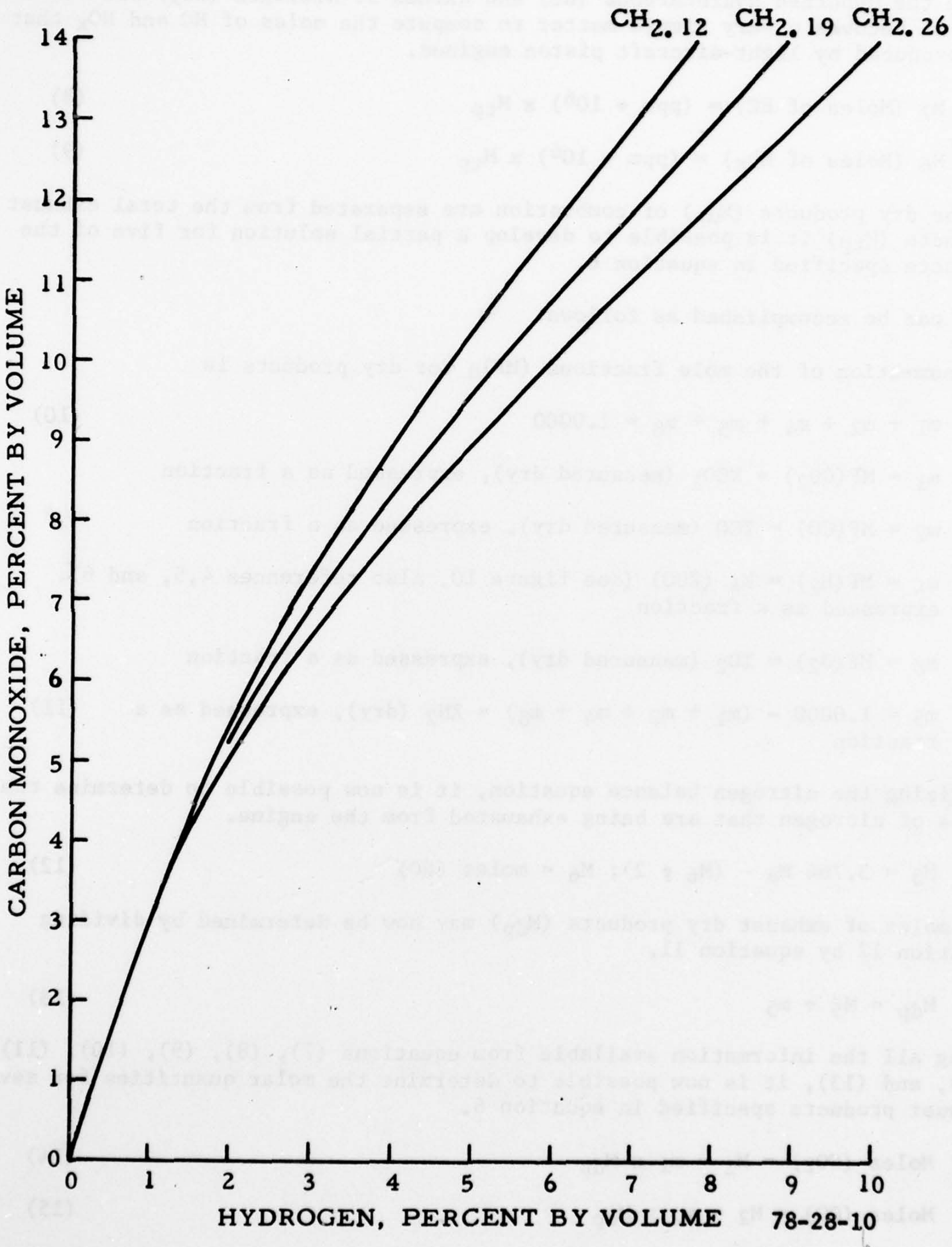


FIGURE 10. RELATION OF CARBON MONOXIDE AND HYDROGEN

$$\text{Moles } (O_2) = M_8 = m_8 \times M_{dp} \tag{18}$$

$$\text{Moles } (CH_4) = M_7 = (\text{ppm} \div 10^6) \times M_{tp} \tag{19}$$

$$\text{Moles } (NO) = M_6 = (\text{ppm} \div 10^6) \times M_{tp} \tag{20}$$

To determine M_3 (Moles of condensed H_2O), it is now appropriate to apply the oxygen balance equation.

$$M_3 = M_a\ (2 + M_w) - (2M_1 + M_2 + M_6 + 2M_8) = \text{Moles } (H_2O) \tag{21}$$

The remaining constituent specified in equation 6 may now be determined from the carbon balance equation 22.

$$M_9 = 8M_f - (M_1 + M_2 + M_7) \tag{22}$$

A check for the total number of exhaust moles (M_{tp}) calculated from equation 9 may now be determined from equation 23.

$$M_{tp} = M_1 + M_2 + M_3 + M_4 + M_5 + M_6 + M_7 + M_8 + M_9 \tag{23}$$

$$\dot{m}_1 + \dot{m}_2 + \dot{m}_3 + \dot{m}_4 + \dot{m}_5 + \dot{m}_6 + \dot{m}_7 + \dot{m}_8 + \dot{m}_9 = 1.0000 \tag{24}$$

$$\dot{m}_1 = MF(CO_2) = M_1 \div M_{tp}$$

$$\dot{m}_2 = MF(CO) = M_2 \div M_{tp}$$

$$\dot{m}_3 = MF(H_2O) = M_3 \div M_{tp}$$

$$\dot{m}_4 = MF(H_2) = M_4 \div M_{tp}$$

$$\dot{m}_5 = MF(N2) = M_5 \div M_{tp}$$

$$\dot{m}_6 = MF(NO) = M_6 \div M_{tp}$$

$$\dot{m}_7 = MF(CH_4) = M_7 \div M_{tp}$$

$$\dot{m}_8 = MF(O_2) = M_8 \div M_{tp}$$

$$\dot{m}_9 = MF(C) = M_9 \div M_{tp}$$

The exhaust constituent mass flow rates may be computed in the following manner using each exhaust constituent's molar constant with the appropriate molecular weight.

$$M_1 \times 44.011 = CO_2 \text{ in lb/h} \tag{25}$$

$$M_2 \times 28.011 = CO \text{ in lb/h} \tag{26}$$

$$M_3 \times 18.016 = H_2O \text{ in lb/h} \tag{27}$$

$$M_4 \times 2.016 = H_2 \text{ in lb/h} \tag{28}$$

$$M_5 \times 28.161 = N_2 \text{ in lb/h} \tag{29}$$

$$M_6 \times 30.008 = NO \text{ in lb/h} \tag{30}$$

$$M_7 \times 16.043 = CH_4 \text{ in lb/h} \tag{31}$$

$$M_8 \times 32.000 = O_2 \text{ in lb/h} \tag{32}$$

$$M_9 \times 12.011 = C \text{ in lb/h} \tag{33}$$

The exhaust fuel flow (W_{fe}), base on exhaust constituents, can now be calculated on a constituent by constituents basis as follows:

$$(M_1 + M_2 + M_9) \times 12.011 = \text{lb/h} \tag{34}$$

$$M_7 \times 16.043 = \text{lb/h} \tag{35}$$

$$\left[(M_3 - M_aM_w) + M_4\right] \times 2.016 = \text{lb/h} \tag{36}$$

$$W_{fe} = (34) + (35) + (36) = \text{lb/h} \tag{37}$$

In a similar manner the exhaust airflow (W_{ae}) can also be calculated on a constituent by constituent basis:

$$M_1 \times 32.000 = \text{lb/h} \tag{38}$$

$$M_2 \times 16.000 = \text{lb/h} \tag{39}$$

$$(M_3 \times 16.000) + M_aM_w \times 18.016) = \text{lb/h} \tag{40}$$

$$M_5 \times 28.161 = \text{lb/h} \tag{41}$$

$$M_6 \times 30.008 = \text{lb/h} \tag{42}$$

$$M_8 \times 32.000 = \text{lb/h} \tag{43}$$

$$W_{ae} = \Sigma\,(38) \longleftrightarrow (45) = \text{lb/h} \tag{44}$$

Using equations (37) and (44) it is now possible to determine a calculated fuel-air ratio on the basis of total exhaust constituents.

$$(F/A)_{calculated} = (37) \div (44) \tag{45}$$

RESULTS

GENERAL COMMENTS.

General aviation piston engine emission tests were conducted to provide the following categories of data:

1. Full-rich (or production fuel schedule) baseline data for each power mode specified in the LTO test cycle.

2. Lean-out data for each power mode specified in the LTO test cycle.

3. Data for the above categories at different spark settings.

4. Data for each power mode specified in the LTO test cycle utilizing different quantities of cooling air.

RESULTS OF BASELINE TESTS (LANDING-TAKEOFF CYCLE EFFECTS).

Based on an analysis of the factors affecting piston engine emissions, it can be shown that the mode conditions having the greatest influence on the gross pollutant levels produced by the combustion process are taxi, approach, and climb when using the LTO cycle defined in tables 3, 4, and 5. The five-mode LTO cycle shows that approximately 99 percent of the total cycle time (27.3 min) is attributed to these three modal conditions. Furthermore, the taxi modes (both out and in) account for slightly less than 59 percent of the total cycle time. The remainder of the time is almost equally apportioned to the approach and climb modes (22 and 18 percent, respectively).

As a result of these time apportionments, it was decided that an investigation and evaluation of the data should be undertaken to determine which mode(s) has the greatest influence on improving general aviation piston engine emissions. The subsequent sections of this report will show the exhaust emissions characteristics for an Avco Lycoming IO-360-A1B6D engine (S/N 888-X) and what improvements are technically feasible within the limits of safe aircraft/engine operational requirements based on sea level propeller test stand evaluations conducted at NAFEC.

The first set of data to be presented and evaluated is the five-mode baseline runs conducted to establish the current production full-rich exhaust emissions characteristics of the IO-360-A1B6D engine. These are summarized in tabular form in appendix C (see tables C-1 through C-17) and includes data that were obtained for a range of sea level, ambient conditions specified as follows:

Induction air temperature (T_i) = 50° F to 115° F
Cooling air temperature (T_c) = $T_i \pm 10°$ F
Induction air pressure (P_i) = 29.20 to 30.50 inHgA
Induction air density (ρ) = 0.0680 to 0.0790 lb/ft^3

Figure 11 presents five-mode baseline data in bargraph form (for different sea level ambient conditions). It also compares the total emissions characteristics of the IO-360-A1B6D engine (current production configuration) with the proposed EPA standards as a function of percent of standard. The data that were utilized to develop figure 11 are tabulated in appendix C and plotted in various forms for analysis and evaluation in figures C-1 through C-19. Tables C-15 and C-16 provide the data tabulation that was used to construct the bargraphs for T_i = 60° F and 95° F.

RESULTS OF LEAN-OUT TESTS.

In the subsequent sections of this report it will be shown what improvements can be achieved as a result of making lean-out adjustments to the fuel metering device: (1) taxi mode only, (2) taxi and approach modes combined, and (3) leaning-out the climb mode to "best power" in combination with taxi and approach mode leaning.

EFFECTS OF LEANING-OUT ON CO EMISSIONS. The test data obtained as a result of NAFEC testing the Avco Lycoming IO-360-A1B6D have been evaluated on the basis of leaning-out the taxi, approach, and climb modes while continuing the operation of the test engine at the production rich and lean limits in the takeoff mode. The results of leaning-out under this procedure are shown in bargraph form in figure 12.

When the taxi modes (out and in) were leaned-out from the production rich or lean limits to a fuel-air ratio of 0.075 or lower, but not lower than stoichiometric (F/A = 0.067) (see figure 12), CO emissions were reduced approximately 20 percent. However, adjustments to the taxi mode fuel schedule alone are not sufficient to bring the total five-mode LTO cycle CO emission level below the proposed federal standard.

Simultaneously, leaning-out both the taxi and approach modes to fuel-air ratios between 0.067 to 0.075 will result in additional improvements in CO emissions. In the case of operating the engine at production rich limits for takeoff and climb while operating taxi and approach at F/A = 0.075, the total five-mode LTO cycle CO emission level will be reduced approximately 50 percent as shown in figure 12.

Additional improvements in the total five-mode LTO cycle for CO emissions can be achieved, as shown in figure 12, if the engine is adjusted to operate at "best power" fuel-air ratios in the climb mode while operating the approach and taxi modes at F/A = 0.075 or lower (not lower than fuel-air ratio = 0.067.)

The preceeding evaluation of CO emissions characteristics was based on the LTO cycle defined by table 5. However, the EPA five-mode LTO cycle defined by table 2 implies that the climb mode power levels can range from 75 to 100 percent. The exhaust emissions produced will be drastically affected. A further examination of the measured data produced at NAFEC show that there is a significant difference in each engine's total LTO cycle emissions output when climbing at 100-percent power compared to climbing at 75-percent power. This

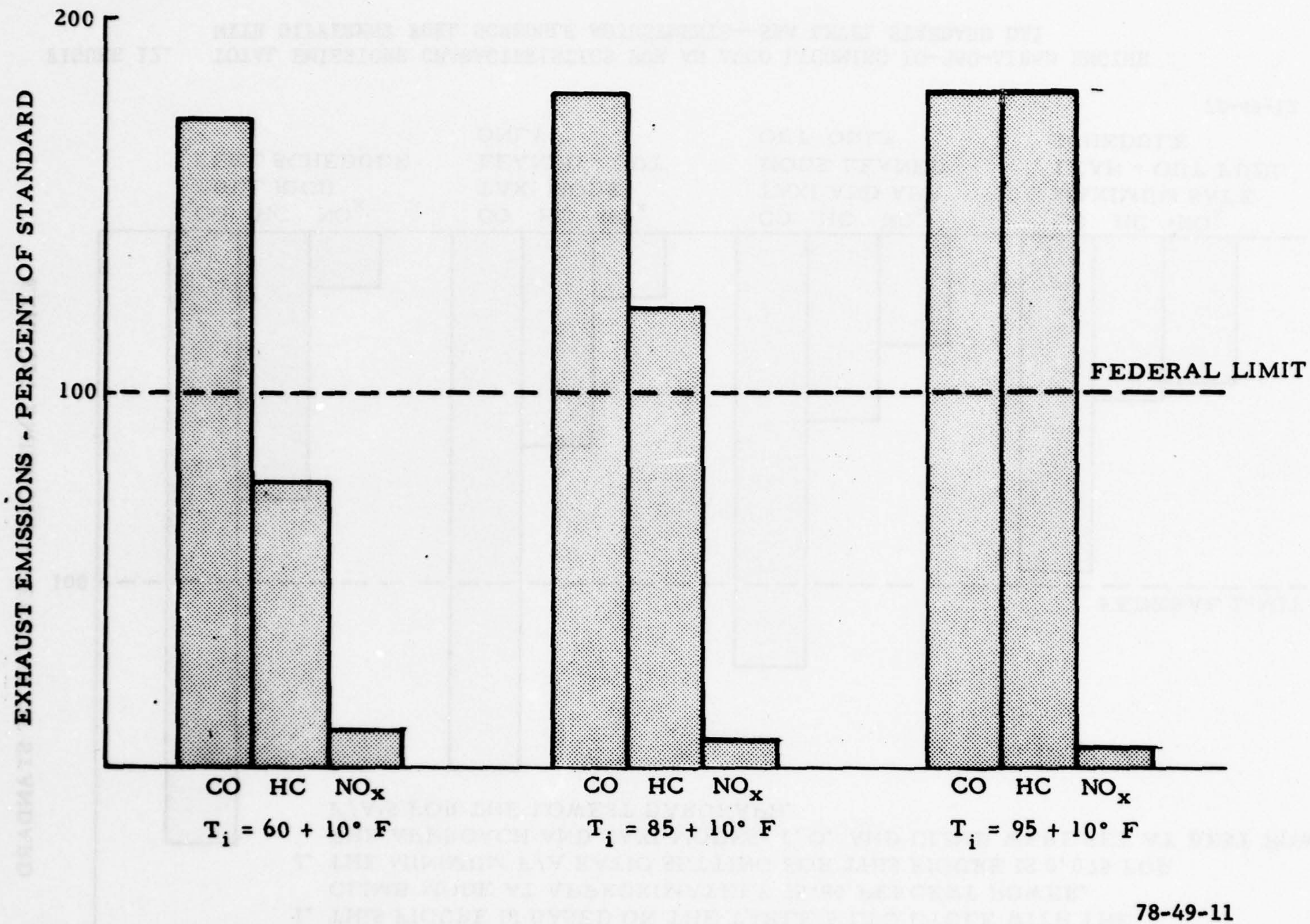


FIGURE 11. AVERAGE TOTAL EMISSIONS CHARACTERISTICS FOR AN AVCO LYCOMING IO-360-A1B6D ENGINE OPERATING UNDER VARYING SEA LEVEL INDUCTION AIR TEMPERATURES--TABLE 5 MINIMUM FIVE-MODE LTO CYCLE

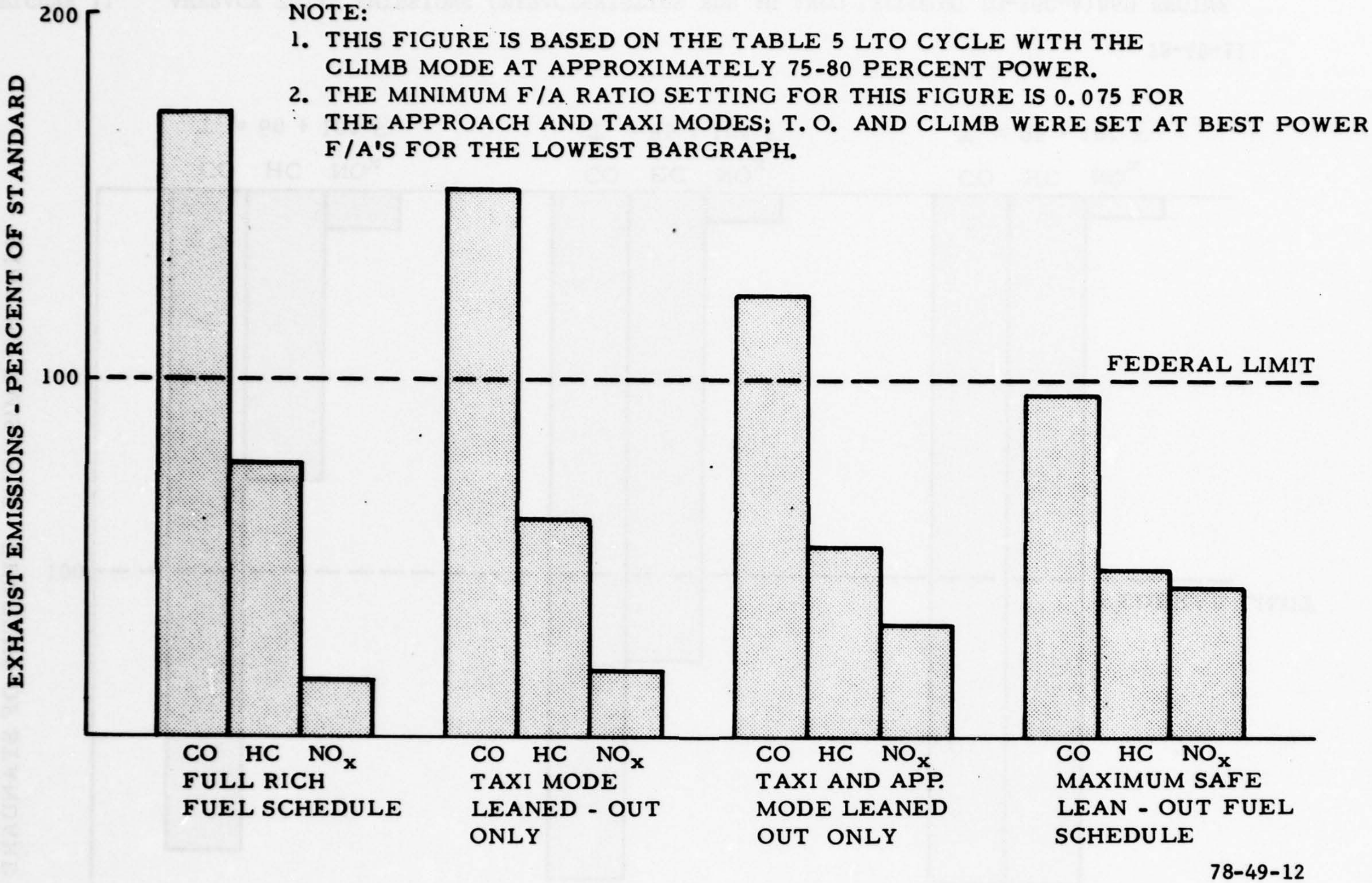


FIGURE 12. TOTAL EMISSIONS CHARACTERISTICS FOR AN AVCO LYCOMING IO-360-A1B6D ENGINE WITH DIFFERENT FUEL SCHEDULE ADJUSTMENTS--SEA LEVEL STANDARD DAY

data evaluation also show that whereas a CO limit of 0.042 pounds per cycle per rated brake horsepower may be achievable as described previously by using the LTO cycle defined by table 5; it is <u>not</u> achieveable using an LTO cycle defined by table 4. When one considers the following safety considerations: (1) sea level, hot-day takeoff requirements with an aircraft at heavy gross weight and (2) altitude takeoff requirements with an aircraft at heavy gross weight, it would appear that the EPA 0.042 limit for CO is not realistic and cannot be complied with, unless engine operational and safety limits are totally ignored.

Table 6 provides a summary of the NAFEC data which indicate what levels of improvement in CO emissions can be achieved by applying simple fuel management techniques (leaning-out by mixture control manipulations), albeit with drastically reduced margins between actual measured maximum cylinder head temperature (CHT) and the maximum CHT limit.

<u>Example</u>: Consider the engine installed in a sea level propeller stand and operating with cooling air at a $\Delta P = 3.0$ inH_2O and the following critical test conditions:

1. Ambient conditions (pressure, temperature, and density)--sea level standard day
2. Fuel schedule--production rich setting
3. Power setting--100%
4. Measured max. CHT--440° F
5. Max. CHT limit--475° F
6. Margin-- 5 minus 4 --35° F

If this engine fuel schedule setting is adjusted to best power (all other parameters constant based on above conditions), the following changes take place:

1. CO emissions are improved by 87% (nominal)
2. Measured max. CHT increases 6.8% (from 440° F to 470° F)
3. Max. CHT limit--475° F
4. Margin-- 3 minus 2 = 5° F
5. Reduction in margin (max. CHT)--(30 ÷ 35) x 100 = 85.7%

Now, if we apply the above results to a sea level hot-day condition, we arrive at the following results:

Production Rich Limit Schedule (100% power)

1. Ambient conditions--sea level hot day
2. Fuel schedule--production rich setting
3. Power setting--100% (nominal)
4. Measured max. CHT--445° F
5. Max. CHT limit--475° F
6. Margin-- 5 minus 4 = 30° F

TABLE 6. SUMMARY OF EXHAUST EMISSIONS (CO) REDUCTION POSSIBILITIES FOR AN AVCO LYCOMING IO-360-A1B6D ENGINE--SEA LEVEL STANDARD DAY (EXCEPT AS NOTED)--COOLING AIR ΔP=3.0 inH_2O

	Modes	F/A	CO lb/Mode	Max. CHT-°F	F/A	CO lb/Mode	Max. CHT-°F	Max. CHT-°F	Max. Limit CHT-°F
1	Taxi	0.0950	2.827	345	0.0750	1.067	-	-	-
2	Takeoff (100%)	0.0960	0.550	440	0.0850	0.375	470	475	475
3	Climb (100%)	0.0960	9.167	440	0.0850	6.250	470	475	475
4	Approach	0.0905	4.480	345	0.0750	2.050	350	355	475
5	lb/Cycle		17.024			9.742			
6	lb/Cycle/RBHP		0.0851			0.0487			
7	Federal Limit		0.042			0.042			
8	Diff. = 6 - 7		0.0431			0.0067			
9	(8 ÷ 7) x 100		102.7			15.0			
10	% of STD = 9 + 100		202.7			116.0			
				This Column For SL. Standard Day			This Column For SL. Standard Day	This Column For SL. Hot Day	
11	Taxi	0.0950	2.827	345	0.0750	1.067	-	-	
12	Takeoff (100%)	0.0960	0.550	440	0.0850	0.375	470	475	475
13	Climb (75-80%)	0.0920	6.667	425	0.0725	4.417	440	435	475
14	Approach	0.0905	4.480	345	0.0750	2.050	350	355	475
15	lb/Cycle		14.524			7.909			
16	lb/Cycle/RBHP		0.0726			0.0395			
17	Federal Limit		0.042			0.042			
18	Diff. = 16 - 17		0.0306			-.0025			
19	(18 ÷ 17) x 100		72.6			-5.8			
20	% of STD = 19 + 100		172.6			94.2			

Best Power Fuel Schedule (100% Power)

1. Ambient conditions--sea level hot day
2. Fuel schedule--best power fuel schedule
3. Power setting--100% (nominal)
4. Measured max. CHT--475° F
5. Max. CHT limit--475° F
6. Margin--5 minus 4 = 0° F
7. Reduction in margin (max. CHT)--(30 ÷ 30) x 100 = 100.0%

EFFECTS OF LEANING-OUT ON HC EMISSIONS. The test data show that the Lycoming engine met the proposed federal standard for a sea level standard day when operating full rich. Leaning-out in the taxi, approach, and climb modes provides added improvements, but is not required to produce HC emission levels below the federal standard (see figure 12). However, it should be noted here that this satisfactory hydrocarbon condition may have been the result of a precedural effect; that is, the engine was cleared out prior to running most of the taxi-out modal tests.

EFFECTS OF LEANING-OUT ON NO_x EMISSIONS. Oxides of nitrogen emissions are not improved as a result of applying lean-out adjustments to the fuel metering devices. In fact, the NO_x levels are at their lowest when the engine is operating full rich as shown in figure 11. Test results have shown that if all the test modes (takeoff, climb, approach, and taxi) were leaned-out excessively (F/A=0.067), the NO_x emission level would exceed the federal standard.

The negative effect on NO_x emissions is one of the reasons why it was decided to evaluate and study the effects of adjusting/manipulating selected mode conditions rather than adopt the philosophy of adjusting all modes.

PARAMETERS EFFECTING CYLINDER HEAD TEMPERATURES. Three basic parameters effect cylinder head temperatures; these are: (1) variable cooling airflow, (2) air temperature, and (3) fuel schedules (rich/lean).

Most general aviation aircraft are designed to operate with cooling air pressure differentials of 4.0 inH_2O or less. The tests conducted with the Avco Lycoming engine utilized 3.0 inH_2O as the basic cooling flow condition. Figures 13 and 14 illustrate the effects of varying the fuel schedule from full rich to best power for takeoff, climb (80%), and approach (40%) while holding the cooling airflow ΔP=3.0 inH_2O. Figure 13 illustrates the sea level, standard-day effects while figure 14 presents the sea level, hot-day (95° F) results.

No tests were conducted with the IO-360-A1B6D engine to investigate the effects of varying the cooling airflow. Therefore, figure 15 (which was extracted from reference 11) was included in this report to illustrate the relative effects that can be achieved when varying the cooling airflow. This figure clearly shows that any attempt to lean-out current production fuel schedules for general aviation piston engines without giving proper priority consideration to the nacelle cooling requirements can result in drastic reductions in cylinder head temperature margins for safe aircraft operation.

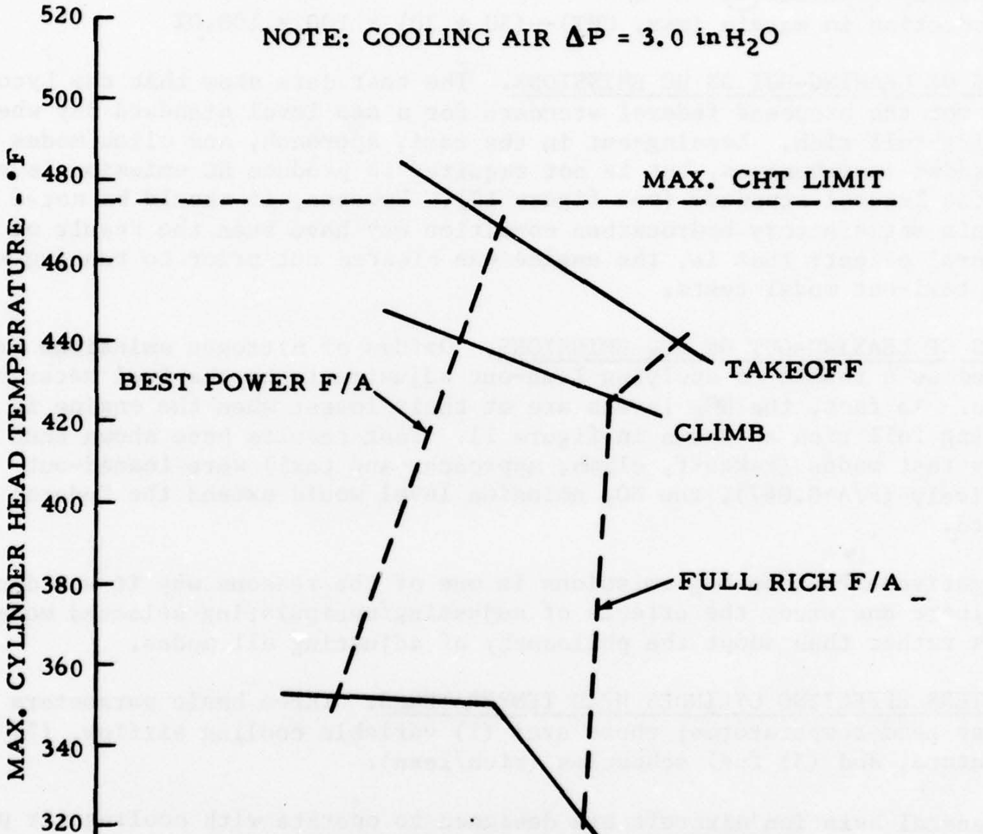


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FIGURE 13. SEA LEVEL STANDARD-DAY MAXIMUM CYLINDER HEAD TEMPERATURES FOR DIFFERENT POWER MODE CONDITIONS AND VARYING FUEL-AIR RATIOS—AVCO LYCOMING IO-360-A1B6D ENGINE

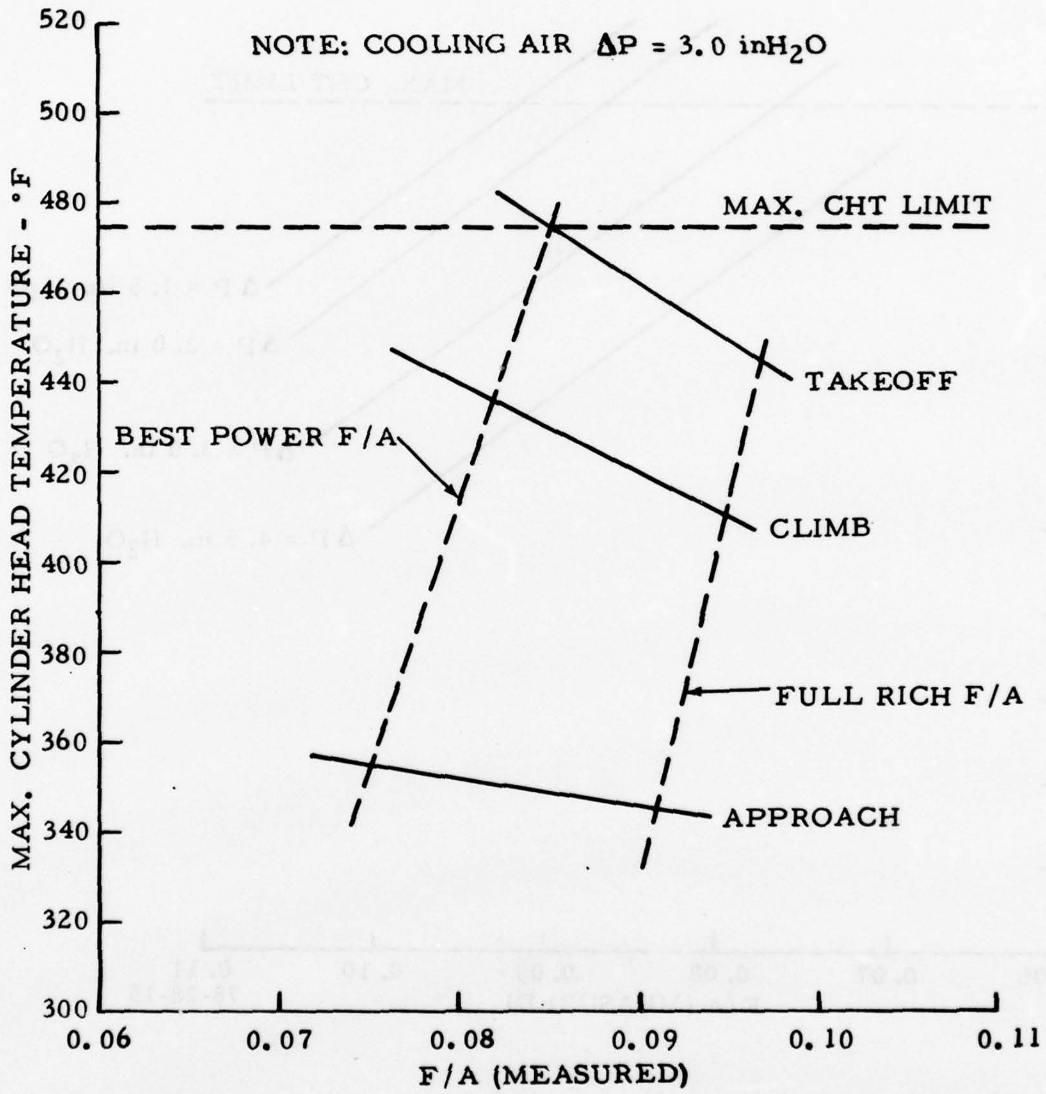

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FIGURE 14. SEA LEVEL HOT-DAY (T_1=95° F) MAXIMUM CYLINDER HEAD TEMPERATURE FOR DIFFERENT POWER MODE CONDITIONS AND VARYING FUEL-AIR RATIOS--AVCO LYCOMING IO-360-A1B6D ENGINE

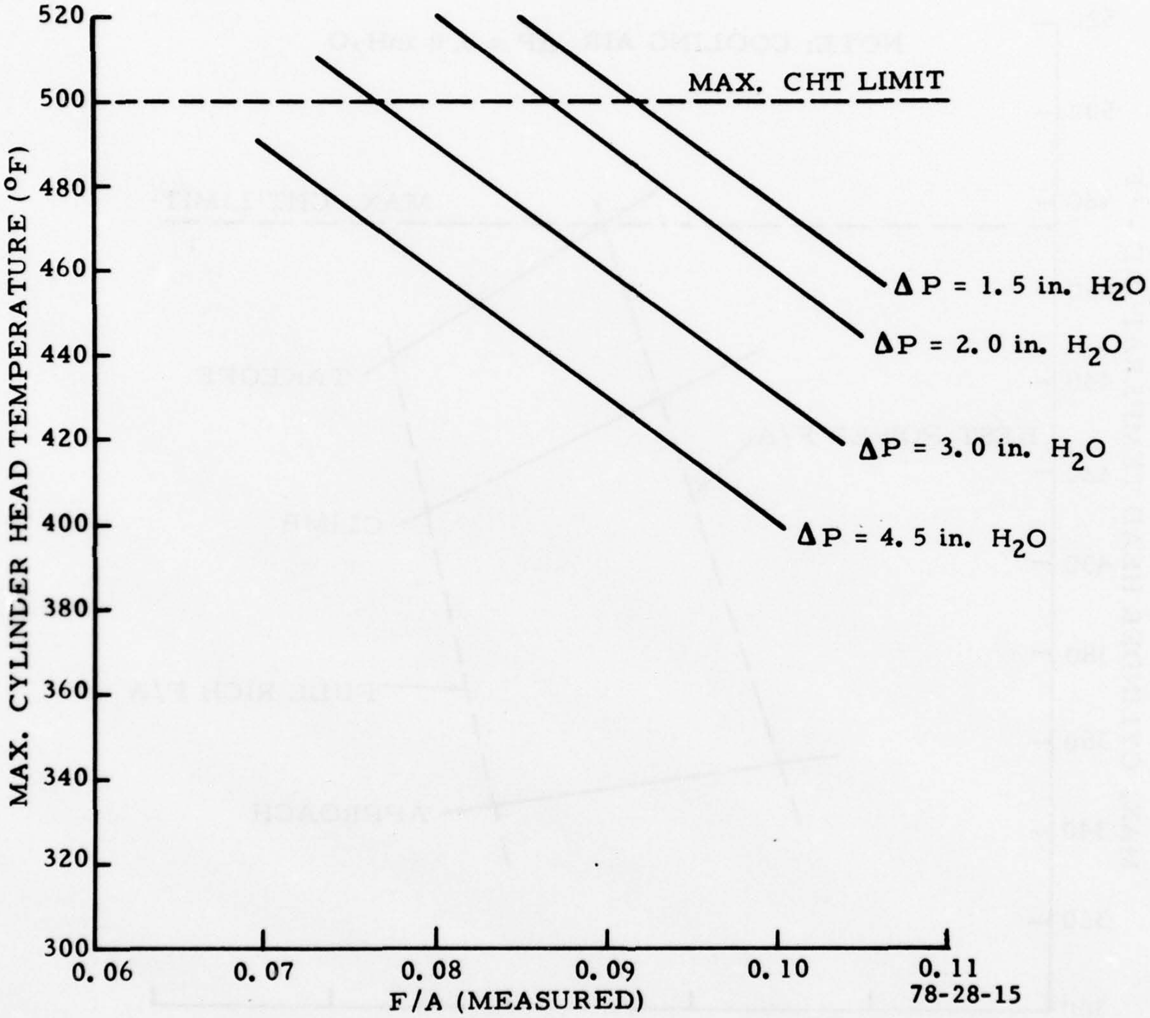

FIGURE 15. SEA LEVEL MAXIMUM CYLINDER HEAD TEMPERATURE VARIATIONS FOR DIFFERENT COOLING AIR DIFFERENTIAL PRESSURE CONDITIONS AND VARYING FUEL-AIR RATIOS--AVCO LYCOMING IO-360-B1BD ENGINE--TAKEOFF MODE

RESULTS OF TESTS WITH VARYING SPARK SETTINGS.

This engine was also evaluated with different spark settings. The basic production setting is 25° before top dead center (BTC). Two other settings were evaluated: 20° BTC and 15° BTC. Table 7 summarizes the results of all the tests conducted and presents the data on an average basis. The three basic power modes (takeoff, climb, and approach—100, 75-80, and 40 percent, respectively) are tabulated using average data based on a minimum of three test runs for each power mode condition and each spark setting.

The results of these tests and the percent changes in emission output are also shown in table 7. For a change in the spark setting from 25° BTC to 20° BTC it may be noted that the CO change is negligible in the takeoff and climb modes for a negligible change in power and a nominal 2.76-percent reduction in maximum CHT. Even though the percent changes in unburned HC and NO_x appear to be significant, it should be noted that both of these pollutants are are being measured on a fraction of a percent basis. Changing the spark setting from 25° BTC to 15° BTC shows that the CO emissions increase (0.03 to 1.68 for takeoff, climb, and approach modes respectively) with a nominal 4.5-percent reduction in power and a 8.0-percent reduction in maximum CHT.

The data presented in table 7 and the plotted results in figures 16 through 21, for the various power conditions and spark setting indicate that the most optimum condition(s) for the IO-360-A1B6D engine is the 20-25° BTC spark settings if it is important not to compromise the available power at the significant modal conditions (takeoff, climb, and approach).

TABLE 7. SUMMARY OF ENGINE PERFORMANCE AND EXHAUST EMISSIONS CHARACTERISTICS FOR THREE DIFFERENT SPARK SETTINGS (°BTC)--FULL-RICH FUEL SCHEDULE

Mode Cond.	RPM	Torque lb-ft 25° BTC	BHP 25° BTC	Ind. Air Temp. (°F)	W_f lb/h	W_a lb/h	F/A	%CO_2	%CO	HC-PPM	NO_x-PPM	Max. CHT (°F)	Run No.
Takeoff	2700	354	182	79	112.8	1173.6	0.0961	8.24	9.74	1625	195	435	16,30,910,924
Climb	2430	311	144	80	86.5	926.0	0.0934	8.24	8.95	1500	230	427	20,31,911,925
Approach	2350	152	68	81	45.4	501.4	0.0905	8.33	9.40	1990	232	356	24,32,912,926
		Torque lb-ft 20° BTC	**BHP 20° BTC**	**Ind. Air Temp. (°F)**									
Takeoff	2700	354	182	78	113.3	1184.8	0.0958	8.30	0.67	1665	184	423	37,50,64
Climb	2430	311	144	77	88.5	943.9	0.0938	8.20	8.95	1500	210	402	38,54,65
Approach	2350	152	68	78	46.5	514.7	0.0903	8.15	9.25	1935	185	343	39,58,66
		Torque lb-ft 15° BTC	**BHP 15° BTC**	**Ind. Air Temp. (°F)**									
Takeoff	2700	338	174	74	114.3	1188.4	0.0962	8.30	9.71	1615	153	399	71,84,98
Climb	2430	303	140	72	90.0	966.0	0.0932	8.07	8.30	1395	180	388	72,88,99
Approach	2300	146	64	70	45.8	515.8	0.0888	8.00	7.72	1686	158	332	92,100

Mode Cond.		Δ Torq.	ΔBHP	ΔCHT(Max)	Nominal Ind. Air Temp. (°F)	%ΔBHP	Δ %CO_2	Δ %CO	Δ HC(%)	Δ NO_x(%)	% ΔCHT(Max)
Takeoff	25°-20° BTC	0	0	-12	78.5	0	+0.06	-0.07	+2.46	-5.64	-2.76
Climb	25°-20° BTC	0	0	-25	78.5	0	-0.04	0	0	-8.70	-5.85
Approach	25°-20° BTC	0	0	-13	79.5	0	-0.18	-0.15	-2.76	-20.26	-3.65
Takeoff	25°-15° BTC	-16	-8	-36	76.5	-4.40	+0.06	-0.03	-0.62	-21.54	-8.28
Climb	25°-15° BTC	- 8	-4	-39	76.0	-2.78	-0.17	-0.65	-7.00	-21.74	-9.13
Approach	25°-15° BTC	- 6	-4	-24	75.5	-5.88	-0.33	-1.68	-15.23	-31.90	-6.74

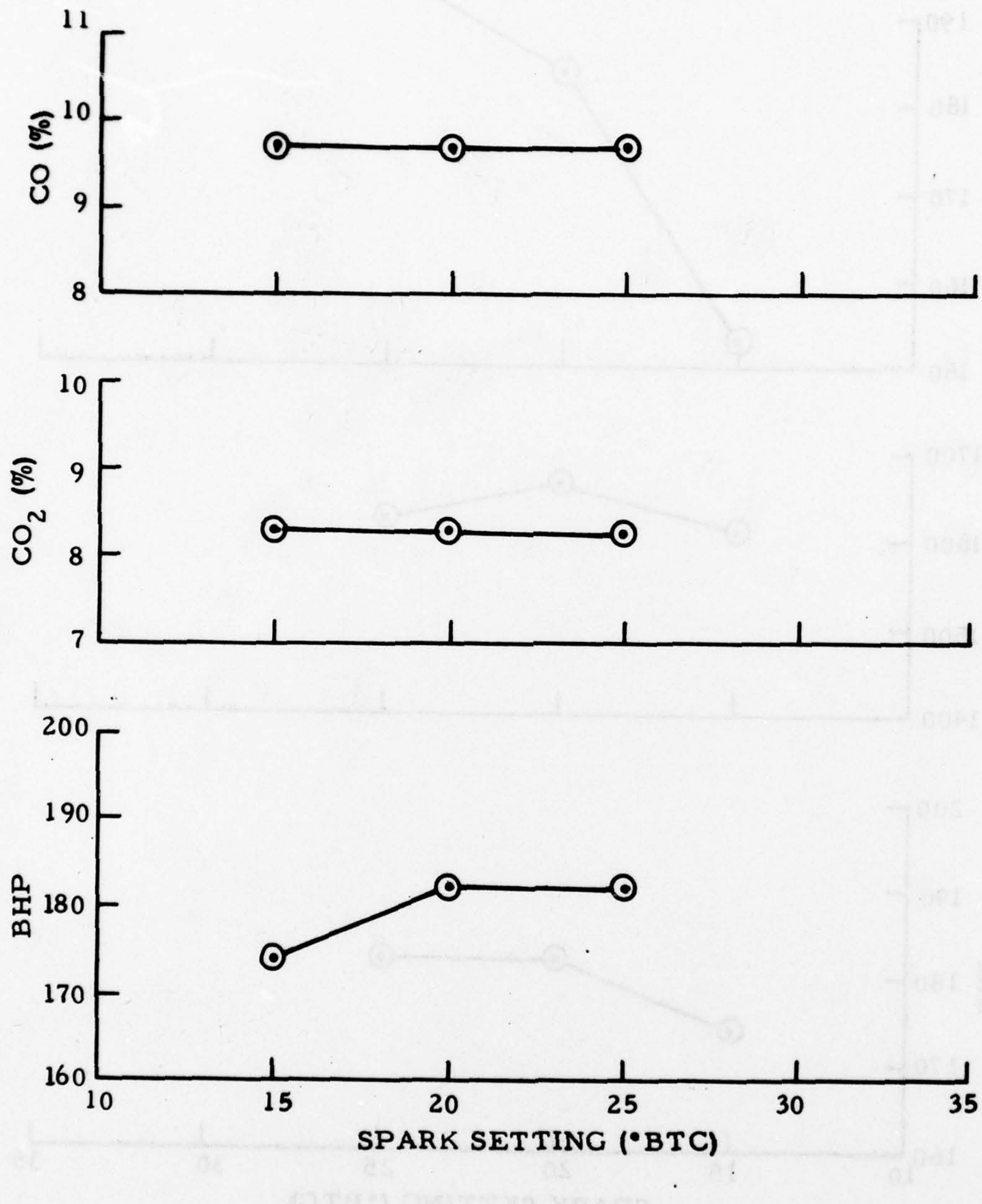

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FIGURE 16. EFFECT OF VARYING SPARK SETTING ON ENGINE PERFORMANCE AND EXHAUST EMISSIONS--TAKEOFF MODE (CO AND CO_2)

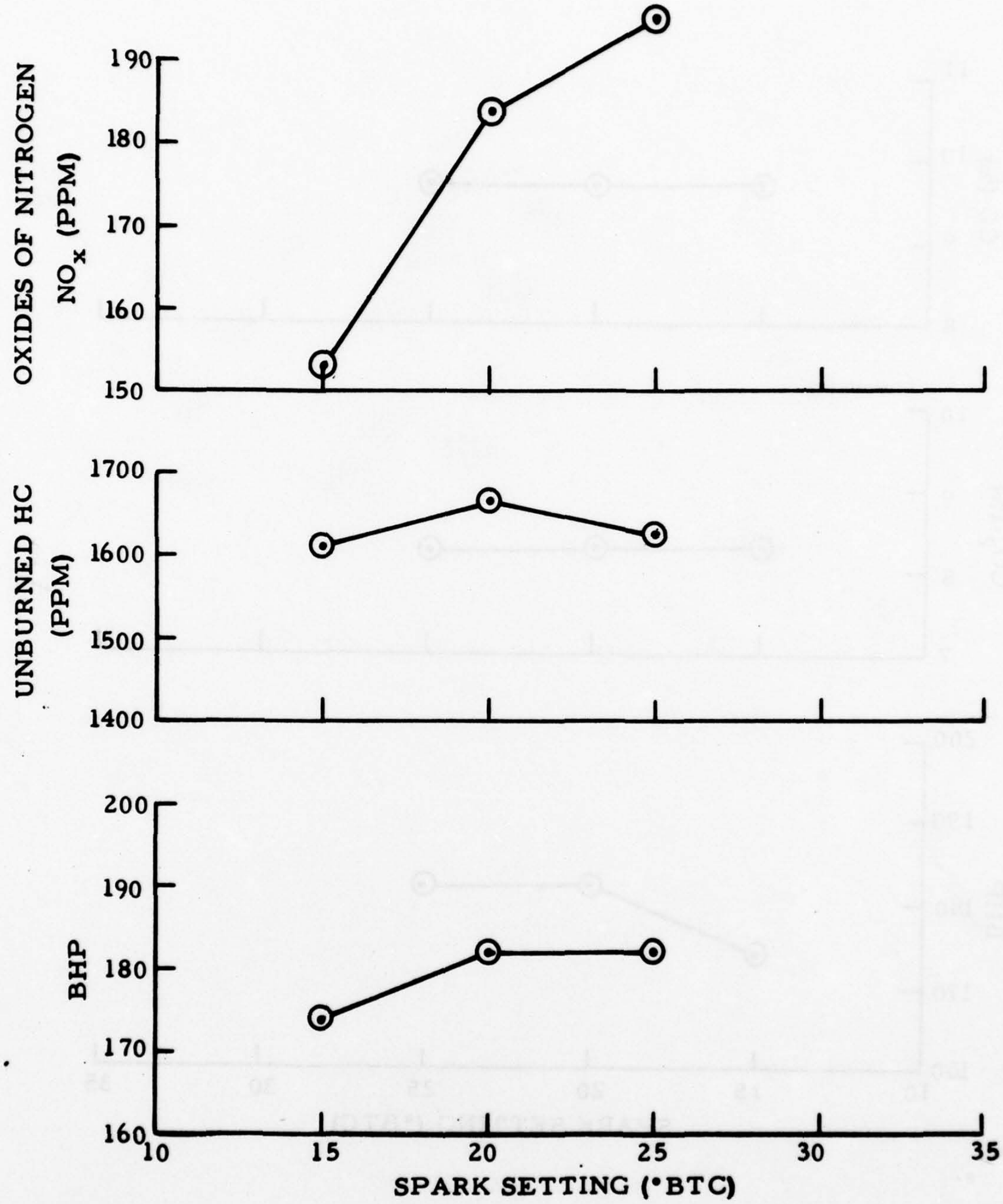

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FIGURE 17. EFFECT OF VARYING SPARK SETTING ON ENGINE PERFORMANCE AND EXHAUST EMISSIONS--TAKEOFF MODE (HC AND NO_x)

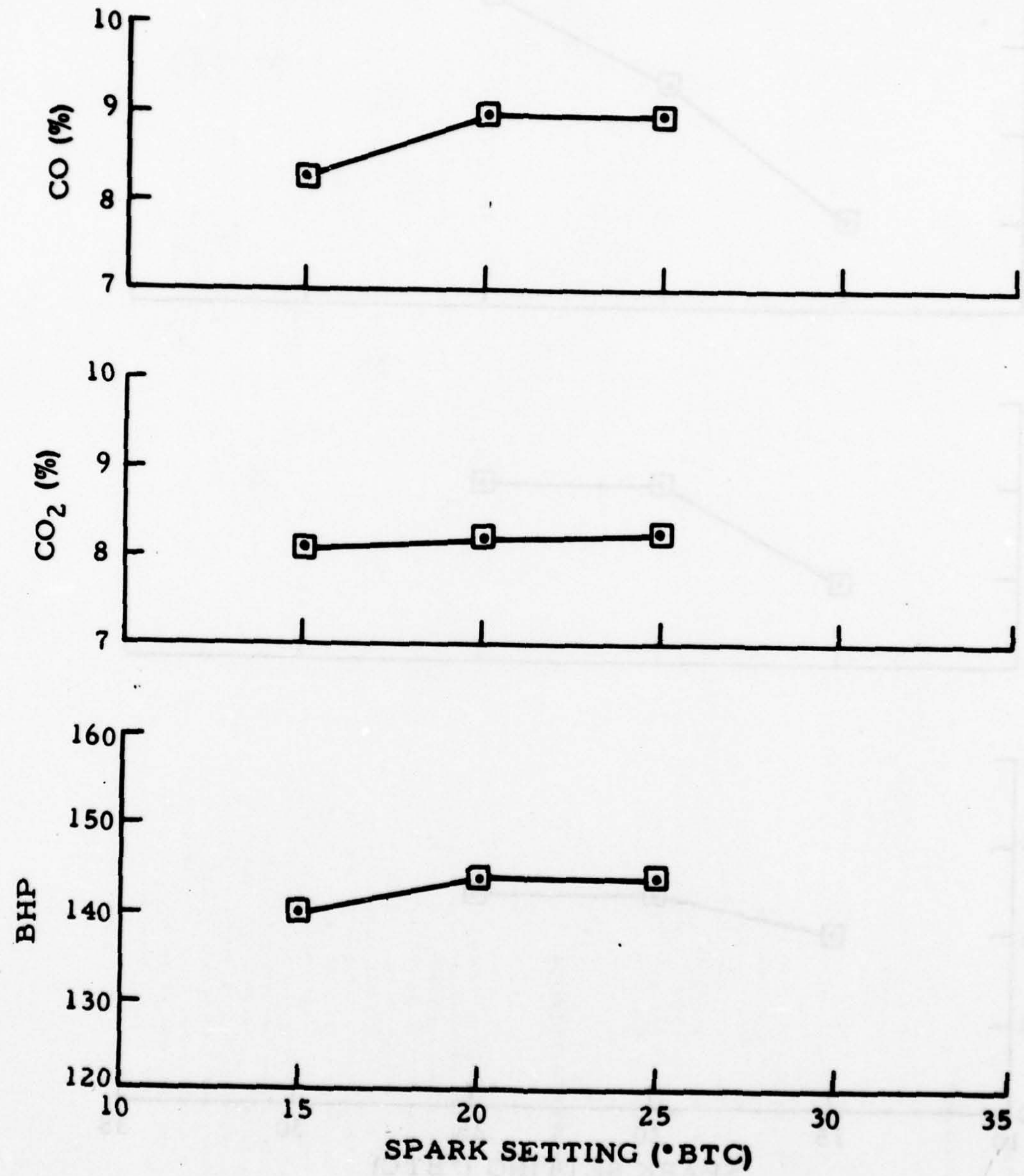

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FIGURE 18. EFFECT OF VARYING SPARK SETTING ON ENGINE PERFORMANCE AND EXHAUST EMISSIONS--CLIMB MODE (CO AND CO_2)

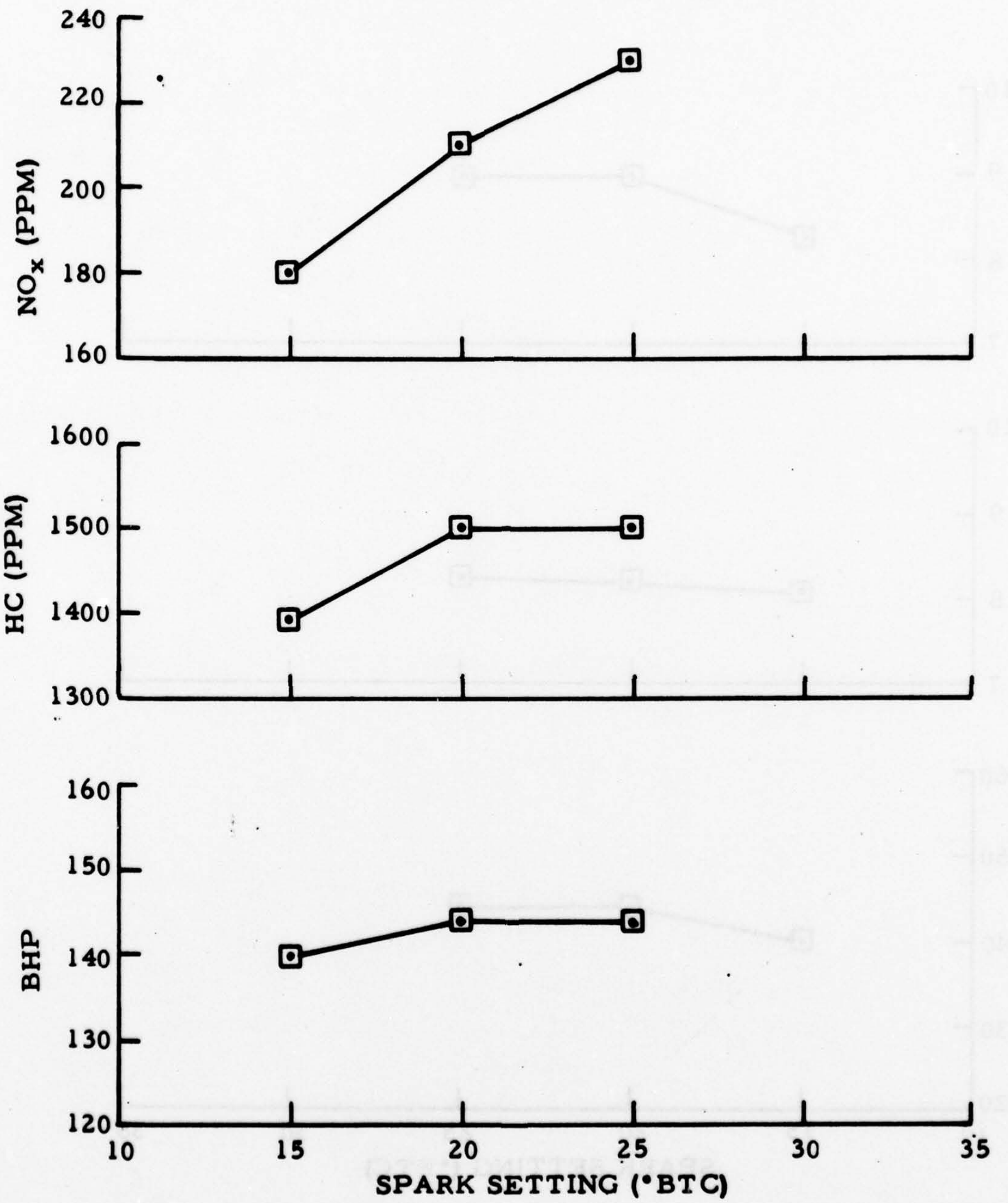

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FIGURE 19. EFFECT OF VARYING SPARK SETTING ON ENGINE PERFORMANCE AND EXHAUST EMISSIONS—CLIMB MODE (HC AND NO_x)

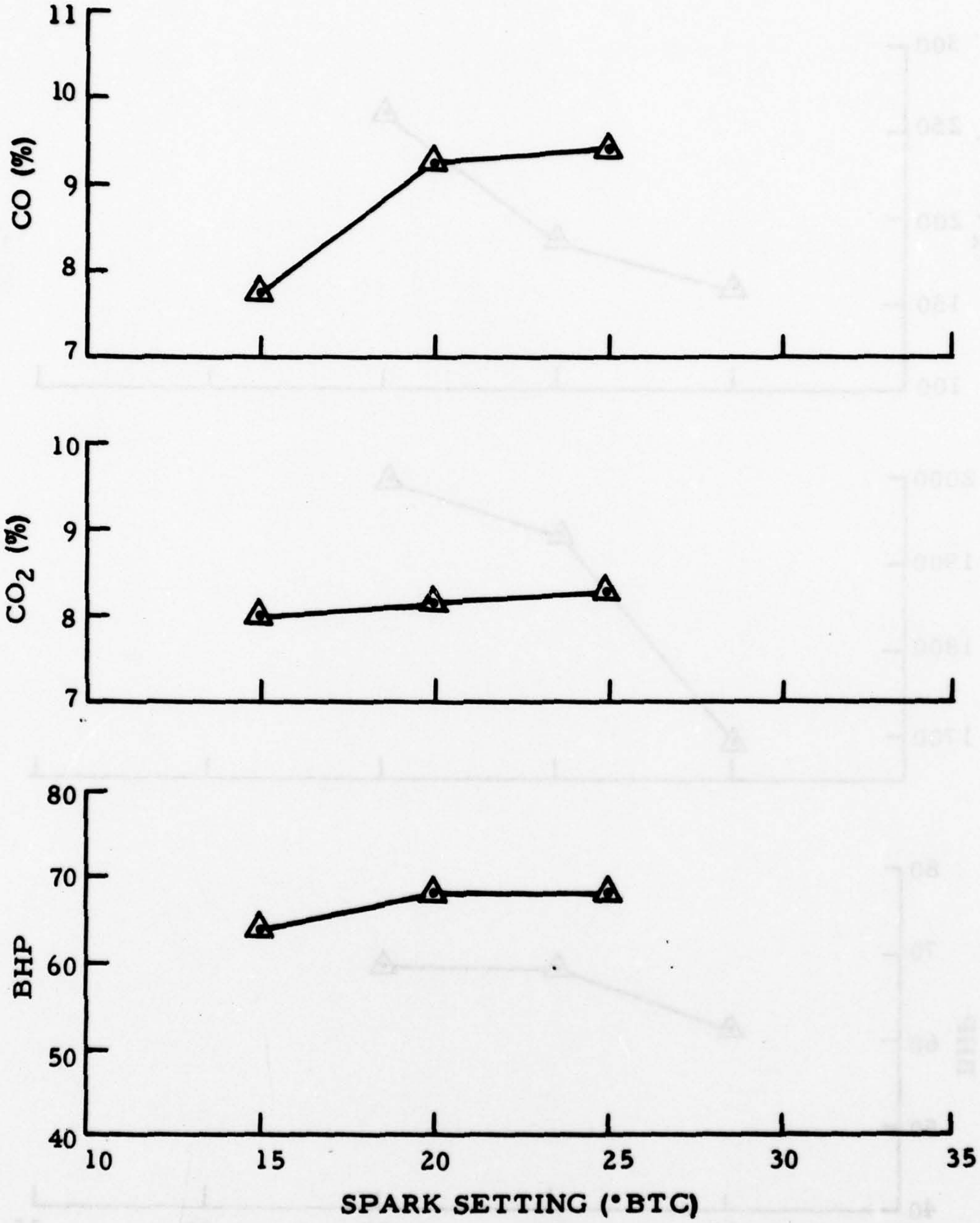

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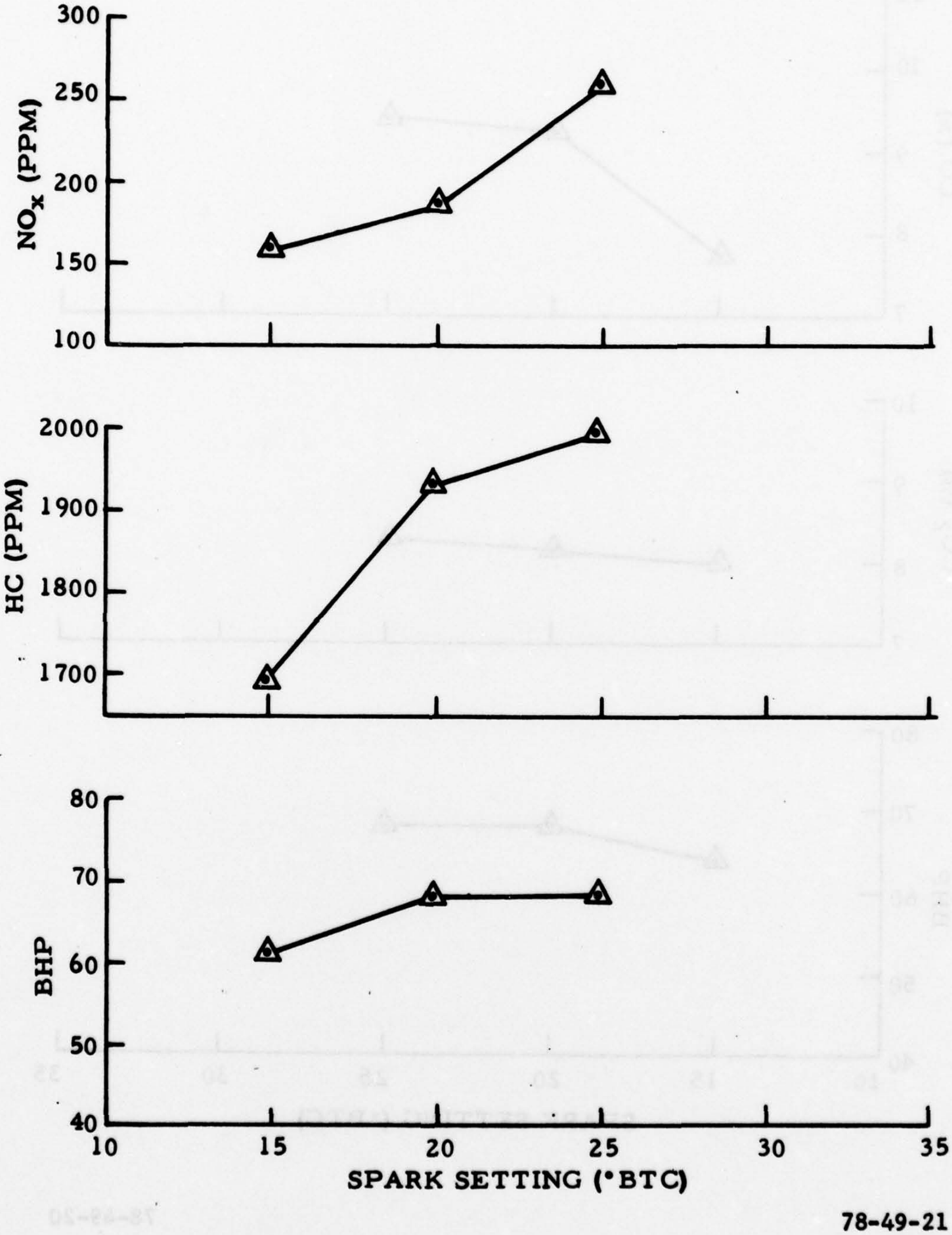
FIGURE 20. EFFECT OF VARYING SPARK SETTING ON ENGINE PERFORMANCE AND EXHAUST EMISSIONS--APPROACH MODE (CO AND CO_2)



78-49-21

FIGURE 21. EFFECT OF VARYING SPARK SETTING ON ENGINE PERFORMANCE AND EXHAUST EMISSIONS—APPROACH MODE (HC AND NO_x)

SUMMARY OF RESULTS

EXHAUST EMISSIONS.

1. The IO-360-A1B6D engine did not meet the proposed EPA carbon monoxide standard for 1979/80, under sea level standard-day conditions.

2. The IO-360-A1B6D engine meets the proposed EPA hydrocarbon and oxides of nitrogen standard for 1979/80 for sea level standard-day conditions.

3. The engine fuel metering device could be adjusted on the test stand to reduce the current CO exhaust emission level, but not to levels required by proposed EPA standards when operating under the most severe LTO cycle requirements.

MAXIMUM CYLINDER HEAD TEMPERATURES.

1. Adjusting the fuel metering device in the takeoff mode to the constant best power operation results in an increase in maximum CHT, which will exceed the engine specification limit on the test stand if cooling air $\Delta P = 3.0$ inH_2O or less.

2. Adjusting the fuel metering device in the climb mode to constant best power operation will result in an increase in maximum CHT. This latter change will necessitate an increase in cooling air flow to provide adequate temperature margins for hot-day operations. An increase in cooling air differential pressure of approximately 1.0 inH_2O may be required for certain critical installations.

3. No critical maximum CHT's result from leaning-out the approach and taxi modes.

CRITICAL LANDING AND TAKEOFF CYCLE.

1. The most critical LTO cycle is the cycle defined in this report as maximum five-mode LTO cycle (table 4). Engine operation in accordance with the maximum five-mode LTO cycle could not be adjusted to meet the proposed EPA emission standards for 1979/80 without exceeding engine maximum CHT limits.

2. Engine operation in accordance with the minimum five-mode LTO cycle (table 5) could be adjusted to meet the proposed EPA emission standards for 1979/80 without exceeding engine maximum CHT limits.

OPTIMUM SPARK SETTING.

1. The 20-25° BTC spark settings produce optimum test results:

   a. Optimum Power
   b. Optimum Maximum CHT
   c. Emissions (CO, HC, and NO_x) compatable with optimum power and acceptable CHT margins.

2. The 15° BTC spark setting produced the lowest HC and NO_x emission levels. However, this setting also resulted in a nominal 4.5 percent decrease in power for the takeoff, climb, and approach modes.

CONCLUSIONS

The following conclusions are based on the testing accomplished with the Avco Lycoming IO-360-A1B6D engine.

1. Simple fuel management adjustments (altering of fuel schedule) do not appear to provide the sole capability to safely reduce light-aircraft piston engine exhaust emissions.

2. The test data indicate that fuel management adjustments must be combined with engine/nacelle cooling modifications before safe and optimum low-emission aircraft/engine combinations can be achieved.

3. Spark settings other than the 20-25° BTC settings do not appear to produce significantly beneficial improvements in exhaust emissions.

4. The EPA CO limit of 0.042 lb/cycle/rated BHP did not appear to be achievable when hot-day takeoff and climb requirements are impacted by aircraft heavy gross weight and the need to pay close attention to CHT limitations.

5. An accessment of the maximum five-mode LTO cycle (table 4) test data indicate that the following standard changes should be made to the proposed EPA emission standards:

Proposed EPA STD. For 1979/1780 (lb/cycle/rated BHP)	Recommended Standard for 1970/80 (lb/cycle/rated BHP)
CO Standard 0.042	0.075
HC Standard 0.0019	0.0025
NO_x Standard 0.0015	0.0015

6. To avoid CHT problems in the takeoff mode (100-percent power), it is advisable not to adjust the fuel metering device. Engine operation in this mode should continue to be accomplished within current production rich/lean limits.

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APPENDIX A

FUEL SAMPLE ANALYSIS

COMBUSTIBLE ELEMENTS IN FUELS (AVIATION FUEL).

1. Carbon and hydrogen are the predominant combustible elements in fuels (aviation type), with small amounts of sulphur as the only other fuel element.

2. Liquid fuels are mixtures of complex hydrocarbons.

3. For combustion calculations gasoline or fuel oil can be assumed have the average molecular formula C_8H_{17}.

Note: The Exxon® data presented in table A-1 may be found in reference 7.

TABLE A-1. TYPICAL SPECIFICATIONS FOR AVIATION FUELS

Item	D910-76 Grade 100/130	Exxon Aviation Gas 100/130	D910-70 Grade 115/145	Exxon Aviation Gas 115/145
Freezing Point, °F	-72 Max.	Below -76	-76 Max.	Below -76
Reid Vapor Press., PSI	7.0 Max.	6.8	7.0 Max.	6.8
Sulfur, % by Weight	0.05 Max.	0.02	0.05 Max.	0.02
Lower Heating Value, BTU/lb	18,720 Min.		18,800 Min.	
Heat of Comb. (NET). BTU/lb		18,960		19,050
Distillation, %Evaporated				
At 167° F (Max.)	10	22	10	21
At 167° F (Min.)	40		40	
At 221° F (Max.)	50	76	50	62
At 275° F (Max.)	90	97	90	96
Distillation End Point	338° F Max.		338° F Max.	
Final Boiling Point °F		319		322
Tel Content, ML/U.S.Gal.	4.0 Max.	3.9	4.6 Max.	4.5
Color	Green	Green	Purple	Purple

4. NAFEC used 100/130 (octane rated) aviation gasoline for the piston engine emission tests. The following analysis of a typical fuel sample (table A-2) made at the U.S. Naval Air Propulsion Test Center (NAPTC), Trenton, N.J. (reference 8).

TABLE A-2. ANALYSIS OF NAFEC FUEL SAMPLE, 100/130 FUEL

Item	NAFEC Sample 100/130	Grade 100/130(MIL-G-5572E) Spec Limits Min.		Max.
Freezing Point, °F	Below -76° F			-76
Reid Vapor Press., PSI	6.12	5.5		7.0
Sulfur % By Weight	0.024			0.05
Lower Heating Value BTU/lb		18,700		
Heat of Comb. (NET) BTU/lb	18,900			
Distillation, %Evaporated			Distillation %Evaporation	
At 158° F	10			
At 167° F (Min)		167° F	10	
At 167° F (Max.)			40	167° F
At 210° F	40			
At 220° F	50			
At 221° F		221° F	50	
At 242° F	90			
At 275° F		275° F	90	
Distillation End Point	313° F			338° F
Specific Gravity @60° F	0.7071	Report		Report
API Gravity @60° F	68.6		No Limit	
Tel Content, ML/U.S. Gal.	1.84			4.60

Computation for the fuel hydrogen-carbon ratio is based on the fuel net heating value, h_f equal to 18,900 BTU/lb and figure A-1.

$C/H = 5.6$

$C = 12.011$

$C_8 = 8 \times 12.011 = 96.088$

$H_y = (96.088) \div 5.6 = 17.159$

$H = 1.008$

$Y = (17.159) \div 1.008 = 17.022$ Use $Y = 17$

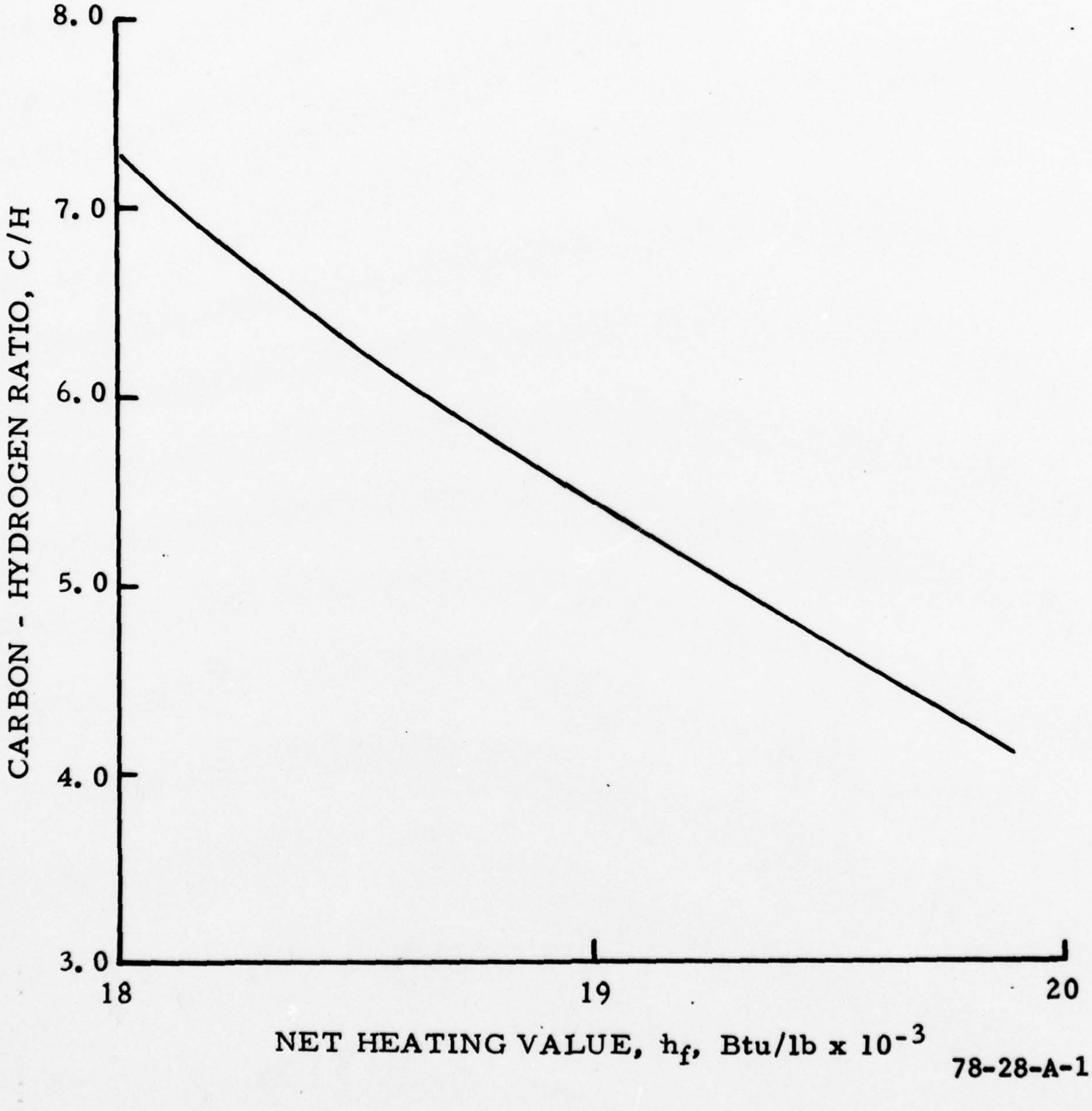

FIGURE A-1. NET HEATING VALUE FOR AVIATION GASOLINE AND CARBON-HYDROGEN RATIO CORRELATION

APPENDIX B

COMPOSITION OF AIR (GENERAL PROPERTIES)

1. Dry air is a mixture of gases that has a representative volumetric analysis in percentages as follows:

Oxygen (O_2)--20.99%
Nitrogen (N_2)--78.03%
Argon (A)--0.94% (Also includes traces of the rare gases neon, helium, and krypton)
Carbon Dioxide (CO_2)--0.03%
Hydrogen (H_2)--0.01%

2. For most calculations it is sufficiently accurate to consider dry air as consisting of:

O_2 = 21.0%
N_2 = 79.0% (including all other inert gases)

3. The moisture or humidity in atmospheric air varies over wide limits, depending on meteorological conditions, its presence in most cases simply implies an additional amount of essentially inert material.

Note: Information given in items 1, 2, and 3 is recommended for computation purposes (reference 3, 4, 9, and 10).

TABLE B-1. MASS ANALYSIS OF PURE DRY AIR

Gas	Volumetric Analysis %	Mole Fraction	Molecular Weight	Relative Weight
O_2	20.99	0.2099	32.00	6.717
N_2	78.03	0.7803	28.016	21.861
A	0.94	0.0094	39.944	0.376
CO_2	0.03	0.0003	44.003	0.013
Inert Gases	0.01	0.0001	48.0	0.002
	100.00	1.000		28.969 = M for air

4. The molecular weight of the <u>apparent nitrogen</u> can be similarly determined by dividing the total mass of the inert gases by the total number of moles of these components:

$$M_{\substack{\text{Apparent}\\\text{Nitrogen}}} = \frac{2225}{79.01} = 28.161$$

5. This appendix advocates the term nitrogen as referring to the entire group of inert gases in the atmosphere and therefore the molecular weight of 28.161 will be the correct value (rather than the value 28.016 for pure nitrogen).

6. In combustion processes the active constituent is oxygen (O_2), and the apparent nitrogen can be considered to be inert. Then for every mole of oxygen supplied, 3.764 moles of apparent nitrogen accompany or dilute the oxygen in the reaction:

$$\frac{79.01}{20.99} = 3.764 \; \frac{\text{Moles Apparent Nitrogen}}{\text{Mole Oxygen}}$$

7. The information given in items 4, 5, and 6 is recommended for computational purposes in reference 4. Therefore, one mole of air (dry), which is composed of one mole of oxygen (O_2) and 3.764 moles of nitrogen (N_2), has a total weight of 137.998 pounds.

$$(O_2 + 3.764\ N_2) = 137.998$$

This gives the molecular weight of air = 28.97.

APPENDIX C

NAFEC TEST DATA AND WORKING PLOTS FOR ANALYSIS AND EVALUATION OF AVCO LYCOMING IO-360-A1B6D ENGINE

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

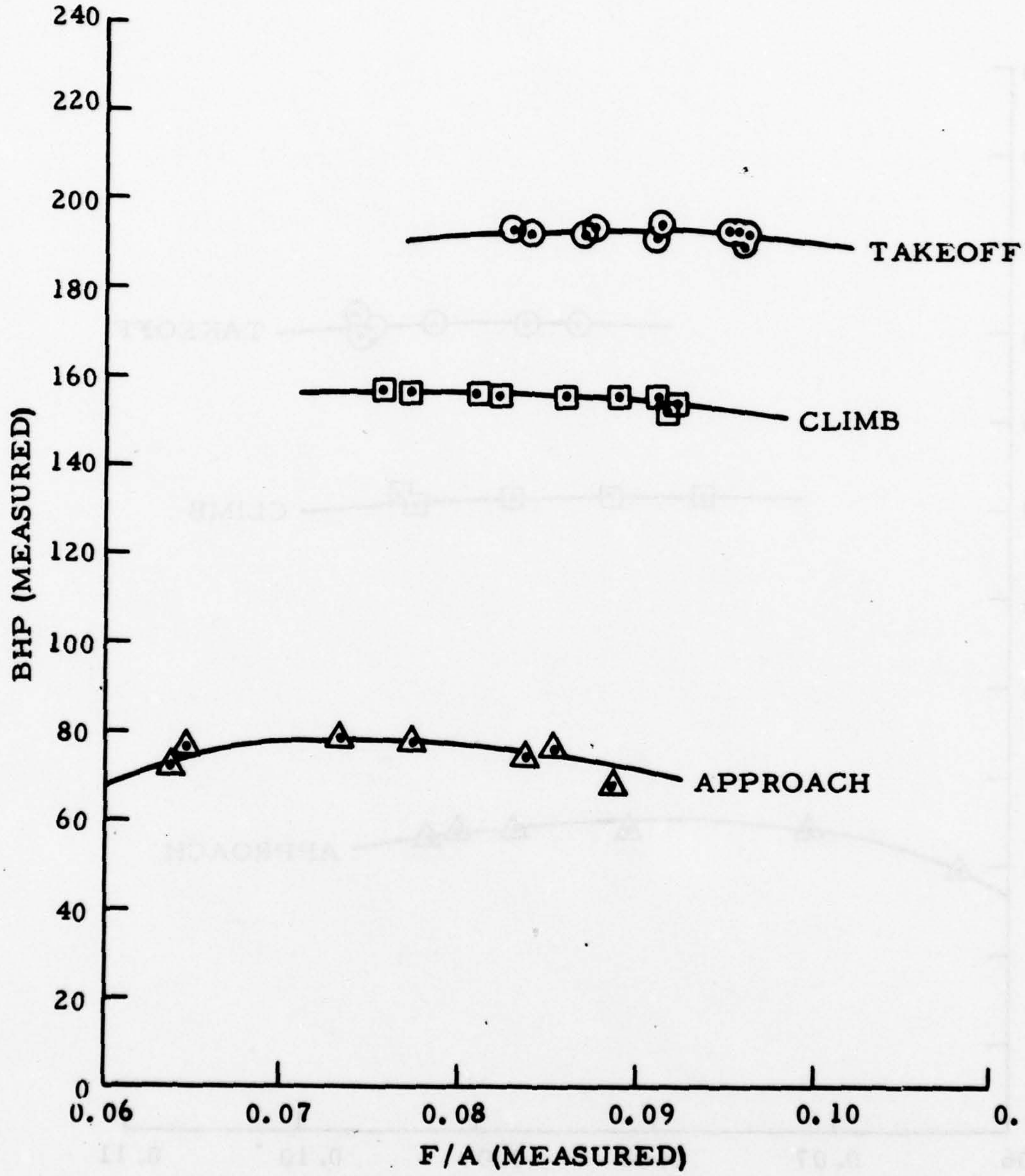

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FIGURE C-1. MEASURED PERFORMANCE--AVCO LYCOMING IO-360-A1B6D ENGINE--TAKEOFF, CLIMB, AND APPROACH MODES--NOMINAL SEA LEVEL AIR DENSITY 0.0771 lb/ft^3

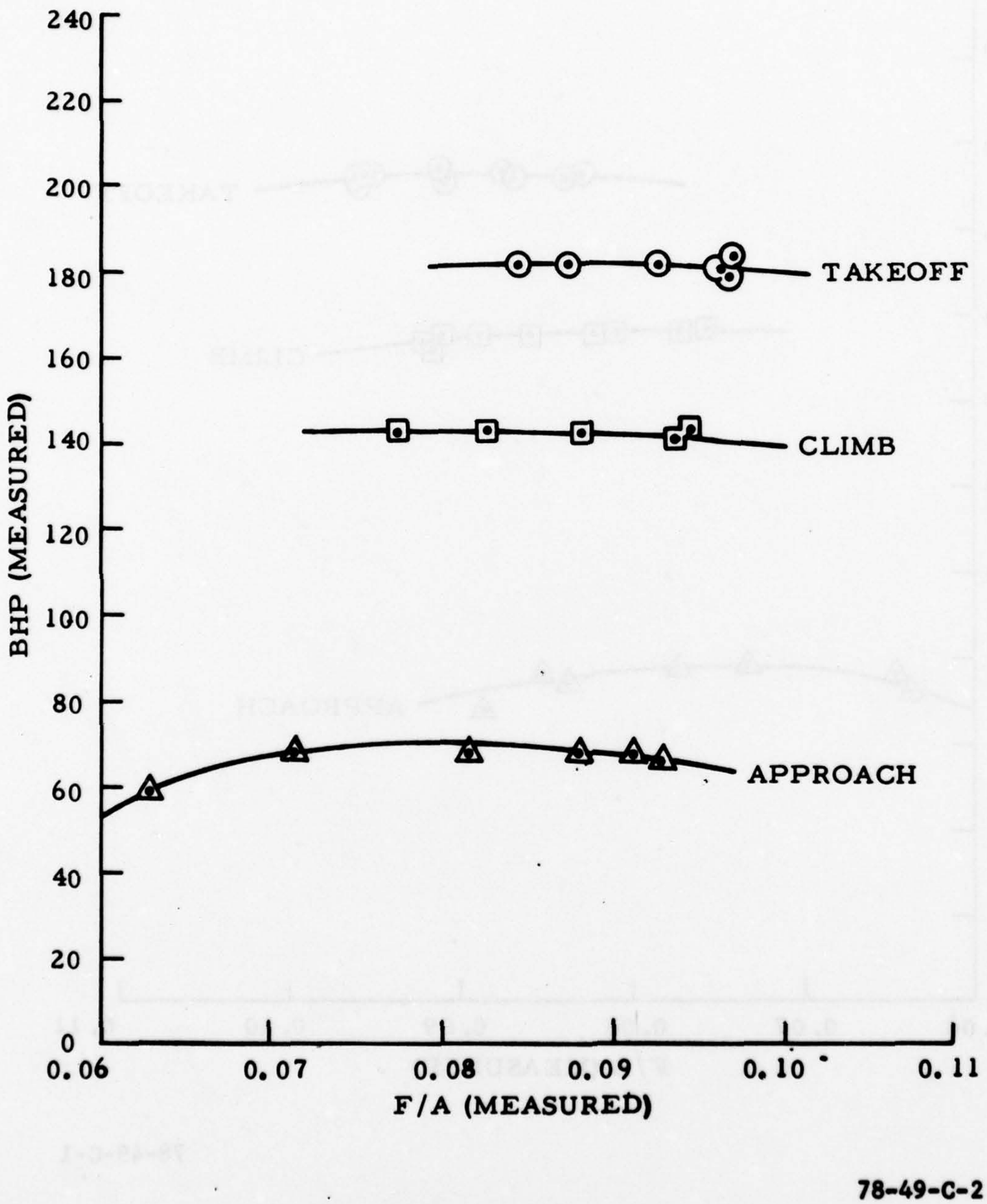

FIGURE C-2. MEASURED PERFORMANCE--AVCO LYCOMING IO-360-A1B6D ENGINE--TAKEOFF, CLIMB, AND APPROACH MODES--NOMINAL SEA LEVEL AIR DENSITY 0.0730 lb/ft^3

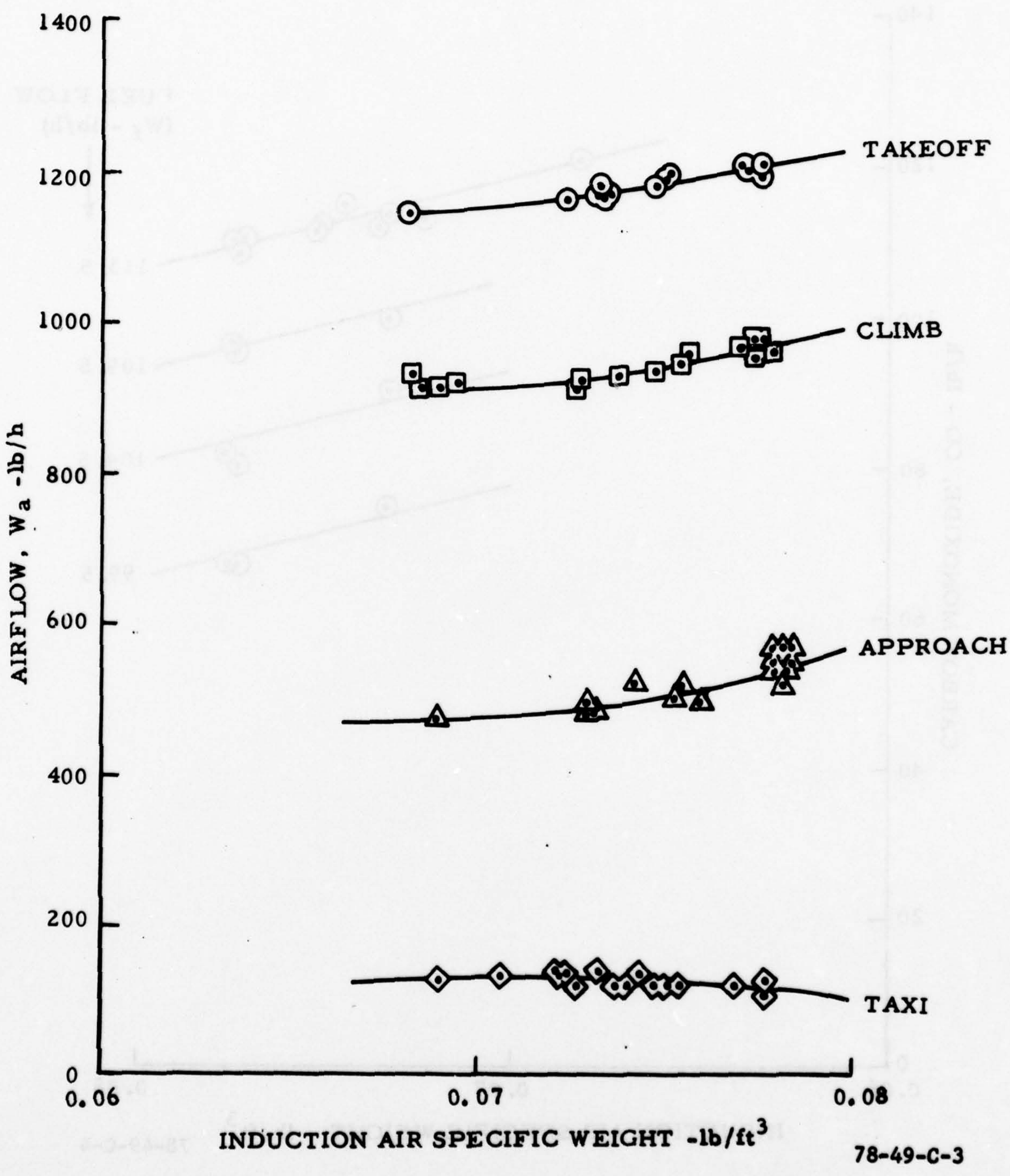

FIGURE C-3. AIRFLOW AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR AN AVCO LYCOMING IO-360-A1B6D ENGINE--NOMINAL SEA LEVEL TEST DATA

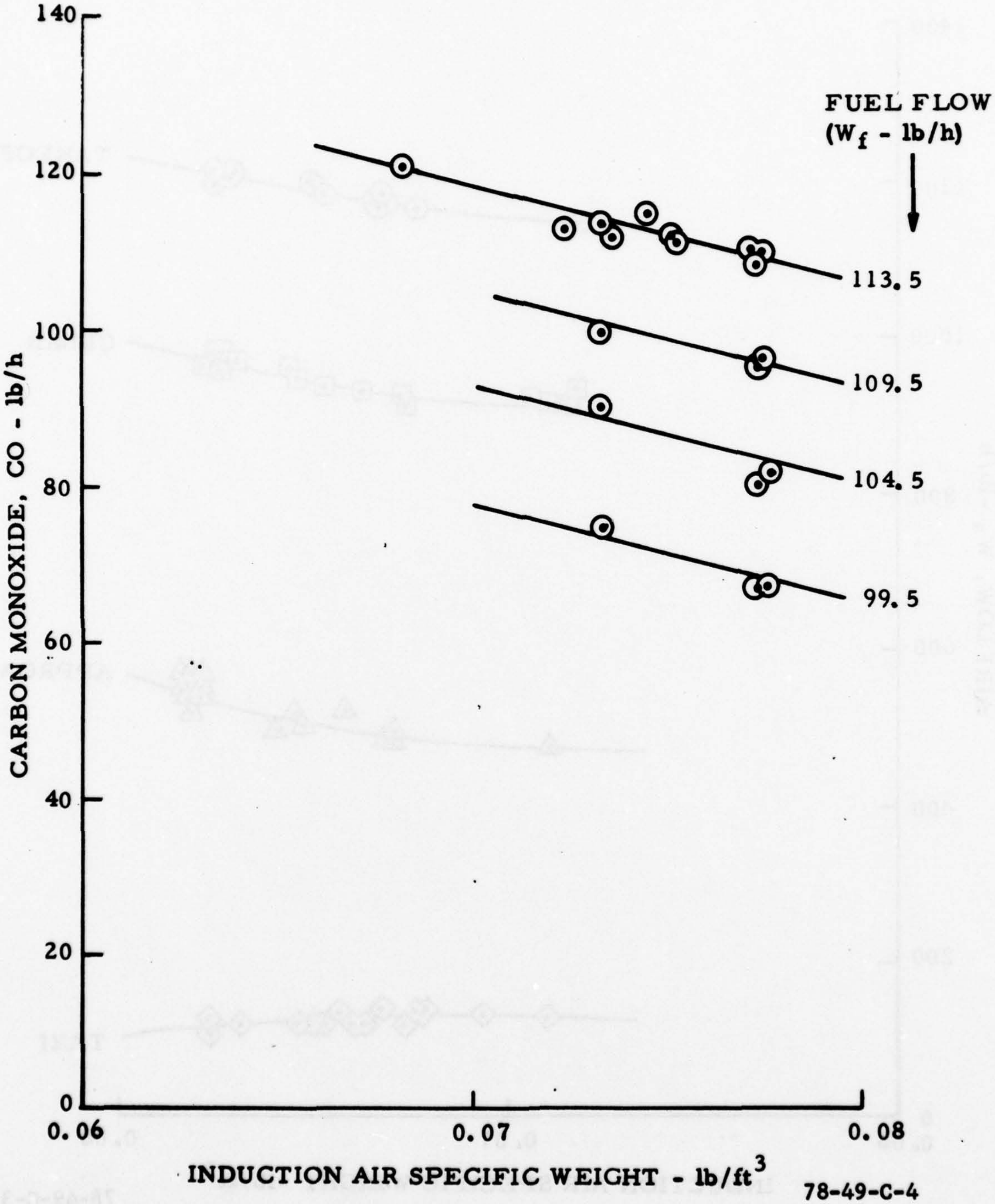

FIGURE C-4. EXHAUST CARBON MONOXIDE AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL TAKEOFF CONSTANT FUEL FLOW SCHEDULES--AVCO LYCOMING IO-360-A1B6D ENGINE

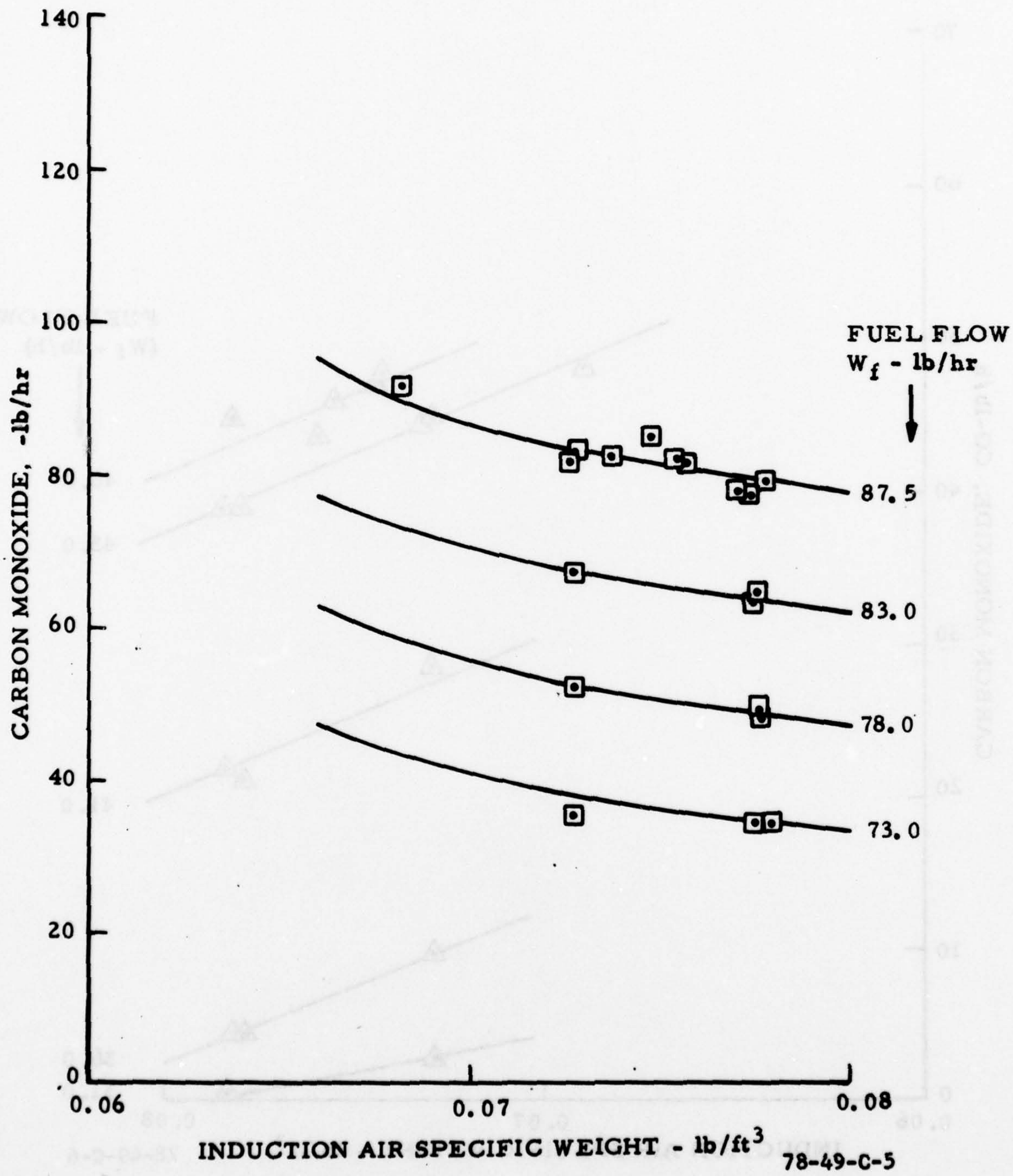

FIGURE C-5. EXHAUST CARBON MONOXIDE AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL CLIMB MODE CONSTANT FUEL FLOW SCHEDULES--AVCO LYCOMING IO-360-A1B6D ENGINE

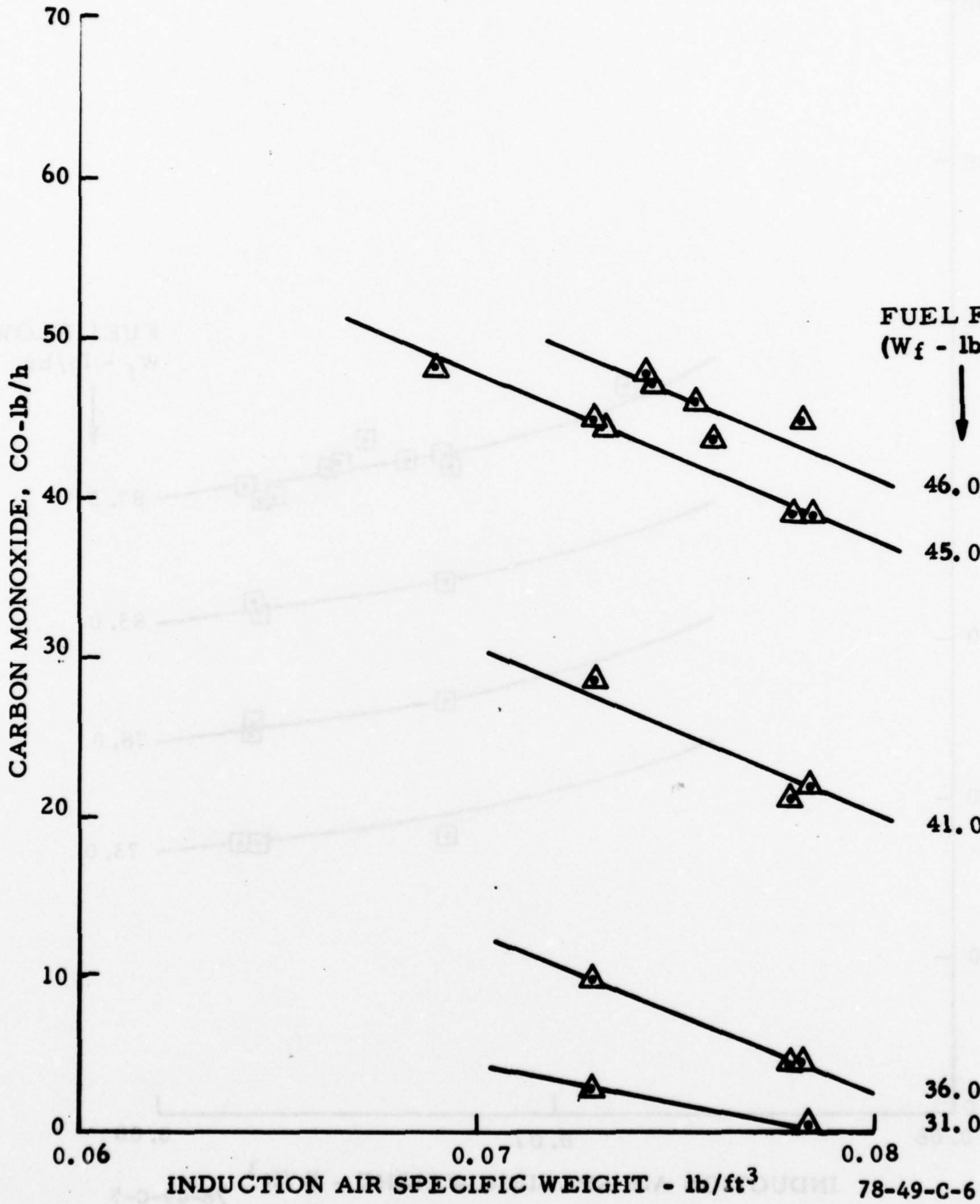

FIGURE C-6. EXHAUST CARBON MONOXIDE AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL APPROACH MODE CONSTANT FUEL FLOW SCHEDULES--AVCO LYCOMING IO-360-A1B6D ENGINE

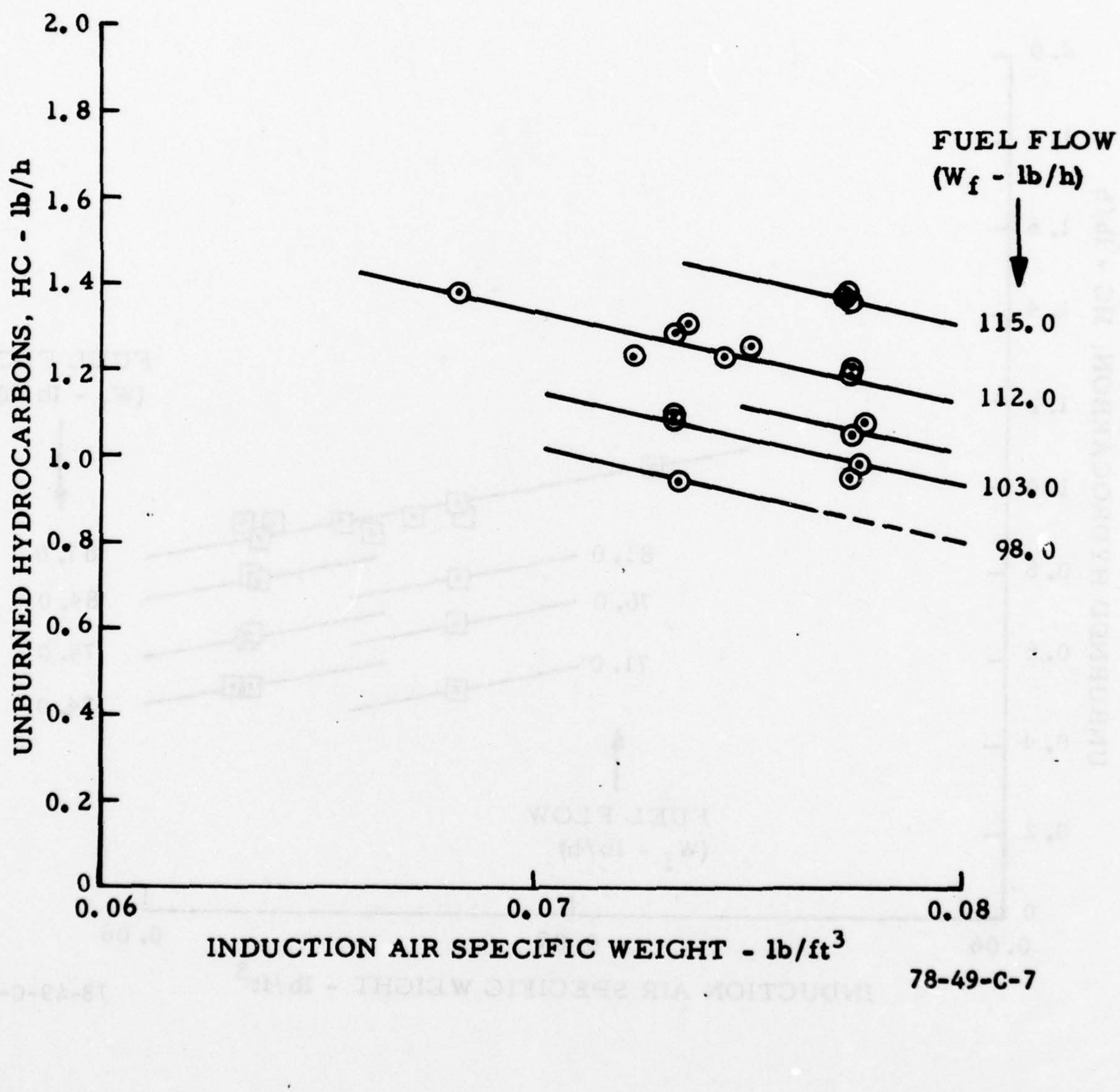

FIGURE C-7. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL TAKEOFF CONSTANT FUEL FLOW SCHEDULES—AVCO LYCOMING IO-360-A1B6D ENGINE

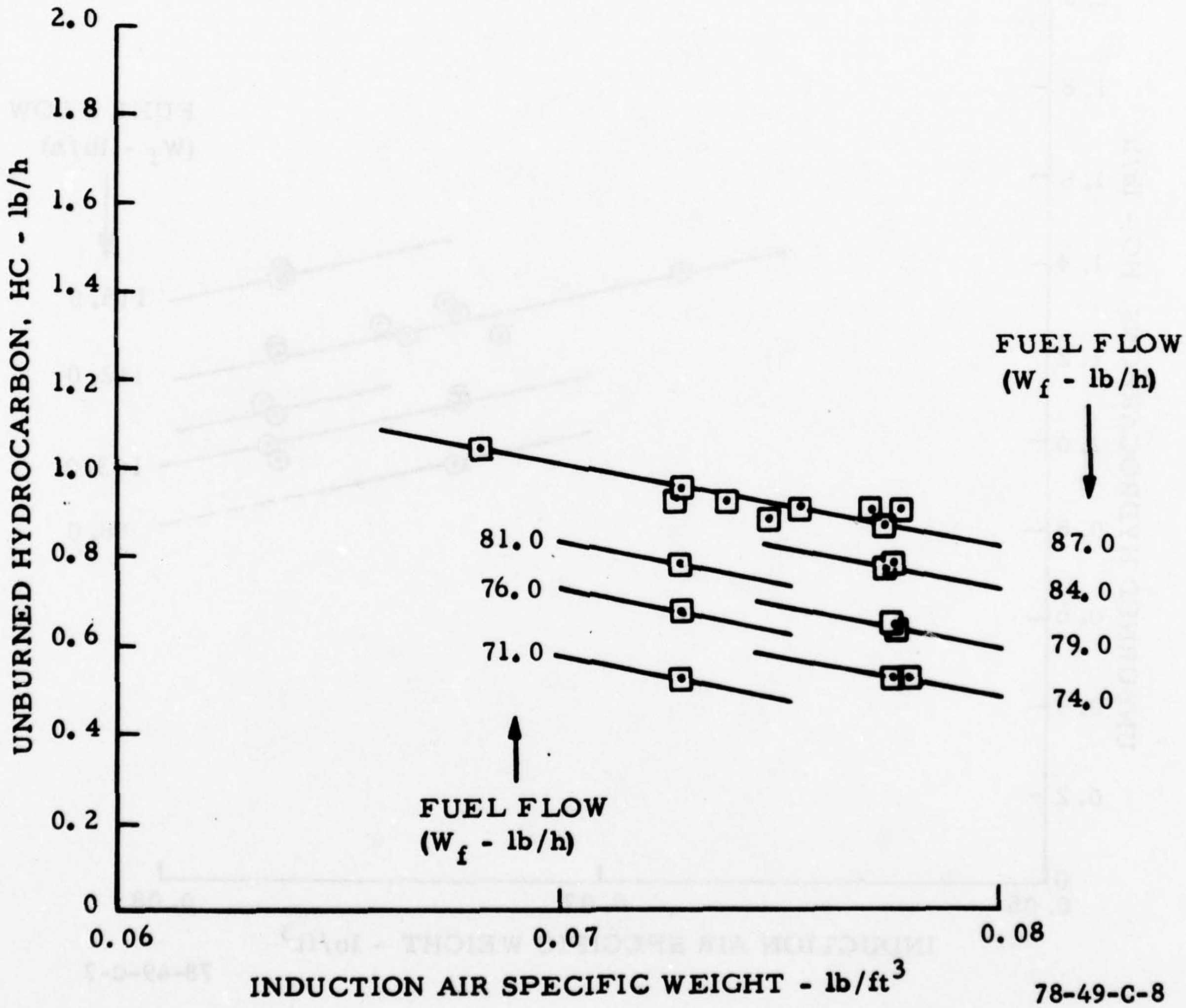

FIGURE C-8. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL CLIMB MODE CONSTANT FUEL FLOW SCHEDULES--AVCO LYCOMING IO-360-A1B6D ENGINE

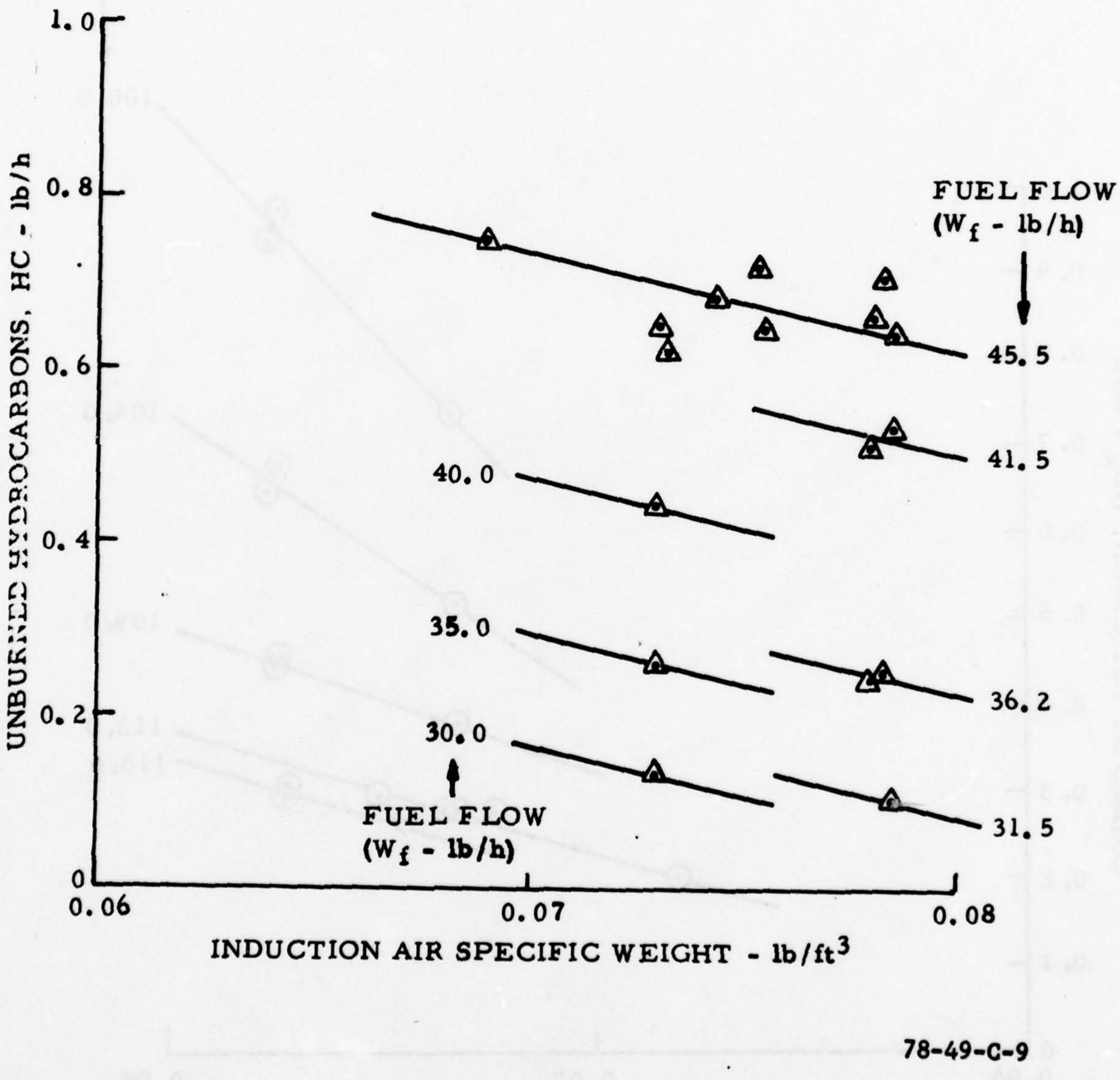

FIGURE C-9. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL APPROACH MODE CONSTANT FUEL FLOW SCHEDULES--AVCO LYCOMING IO-360-A1B6D ENGINE

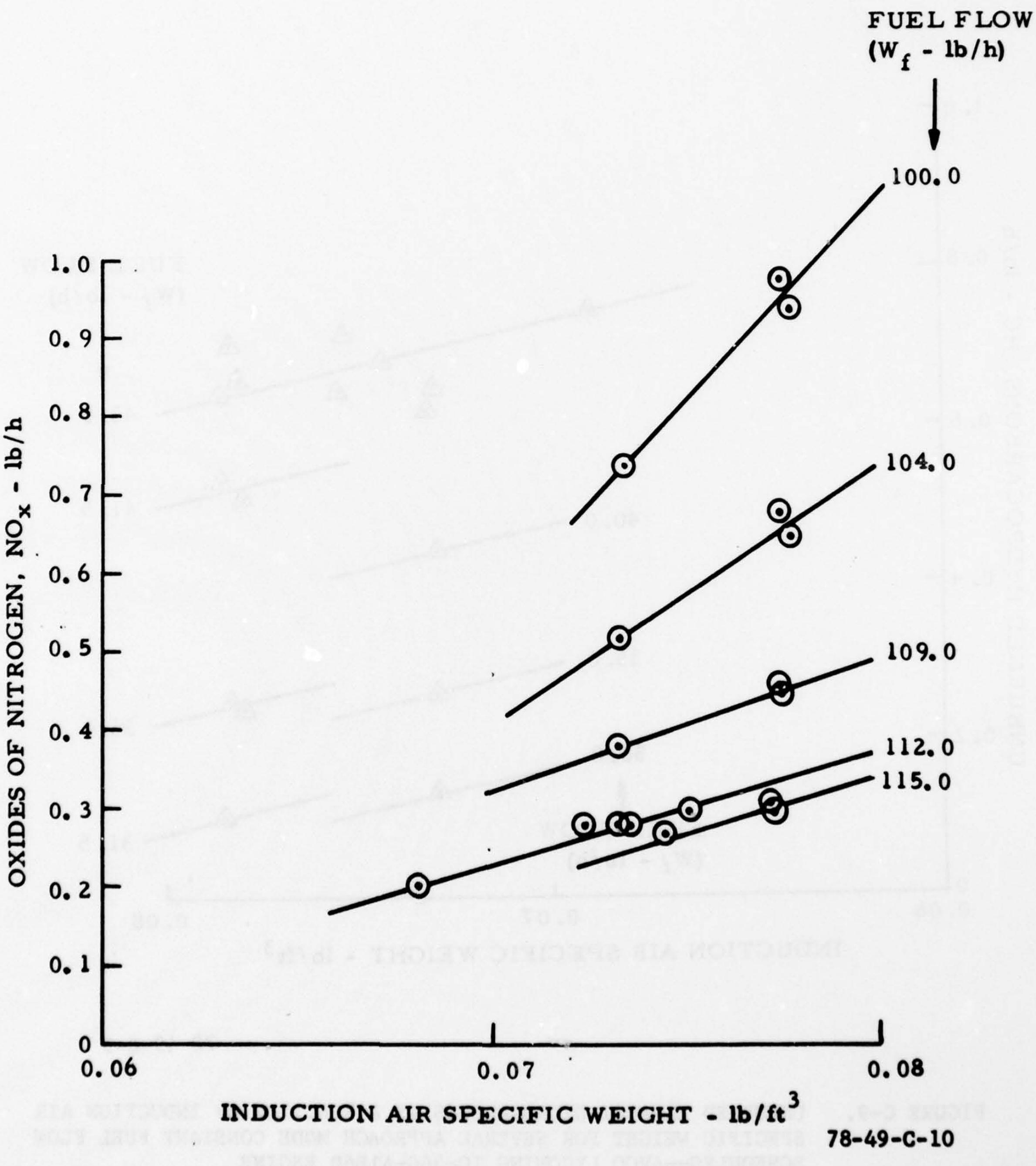

FIGURE C-10. OXIDES OF NITROGEN (NO_x) AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL TAKEOFF CONSTANT FUEL FLOW SCHEDULES--AVCO LYCOMING IO-360-A1B6D ENGINE

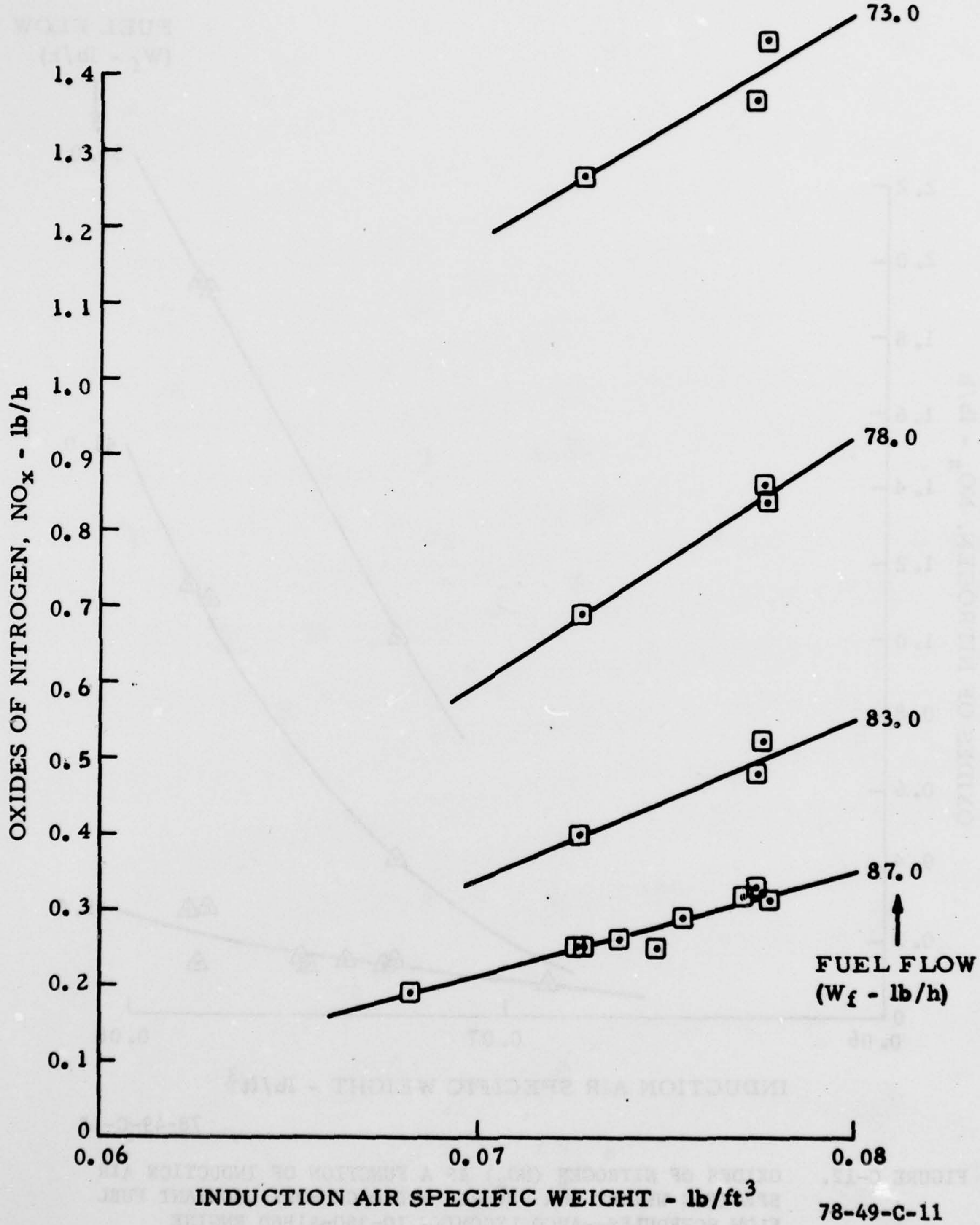

FIGURE C-11. OXIDES OF NITROGEN (NO_x) AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL CLIMB MODE CONSTANT FUEL FLOW SCHEDULES—AVCO LYCOMING IO-360-A1B6D ENGINE

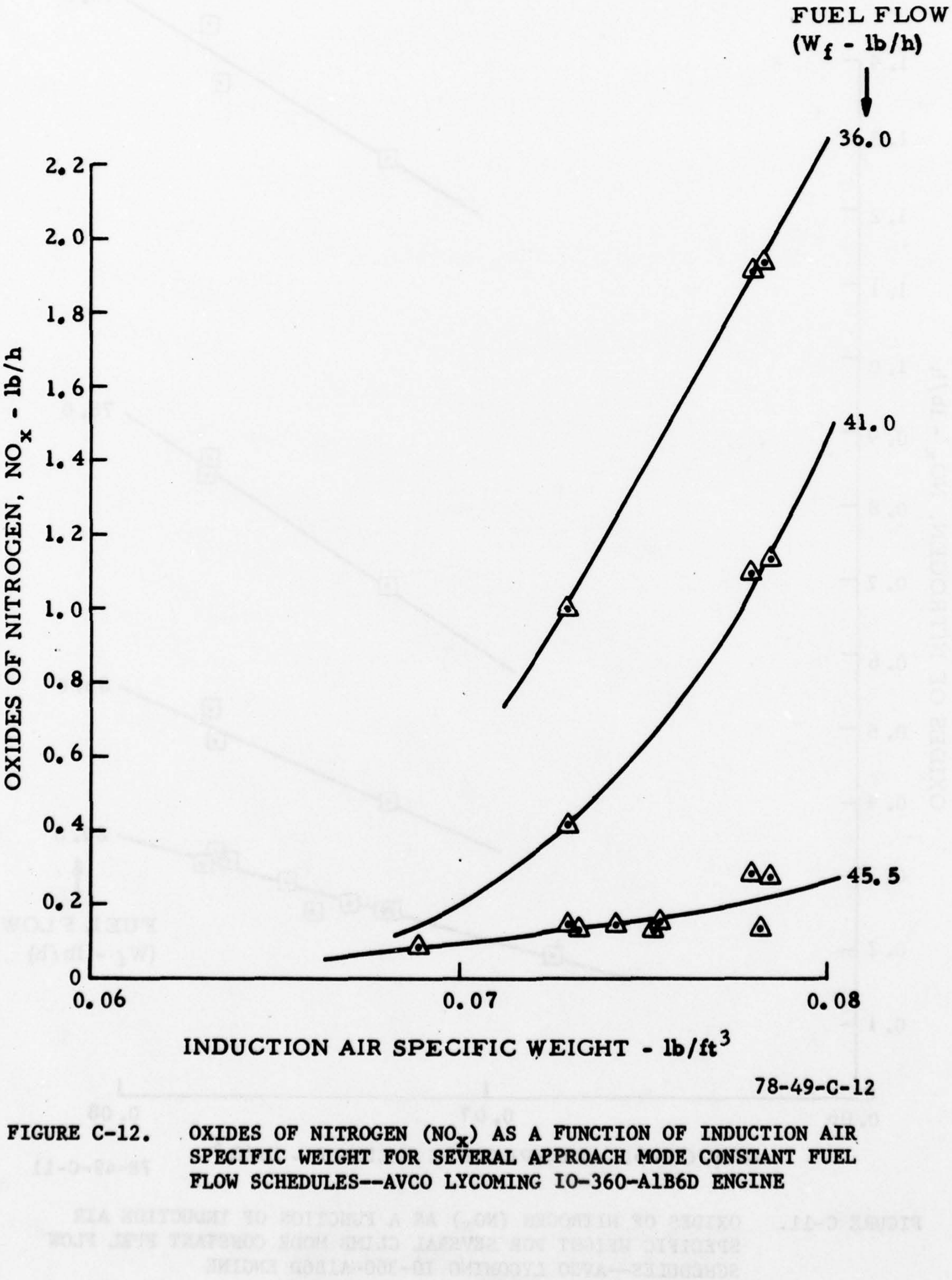

FIGURE C-12. OXIDES OF NITROGEN (NO_x) AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL APPROACH MODE CONSTANT FUEL FLOW SCHEDULES--AVCO LYCOMING IO-360-A1B6D ENGINE

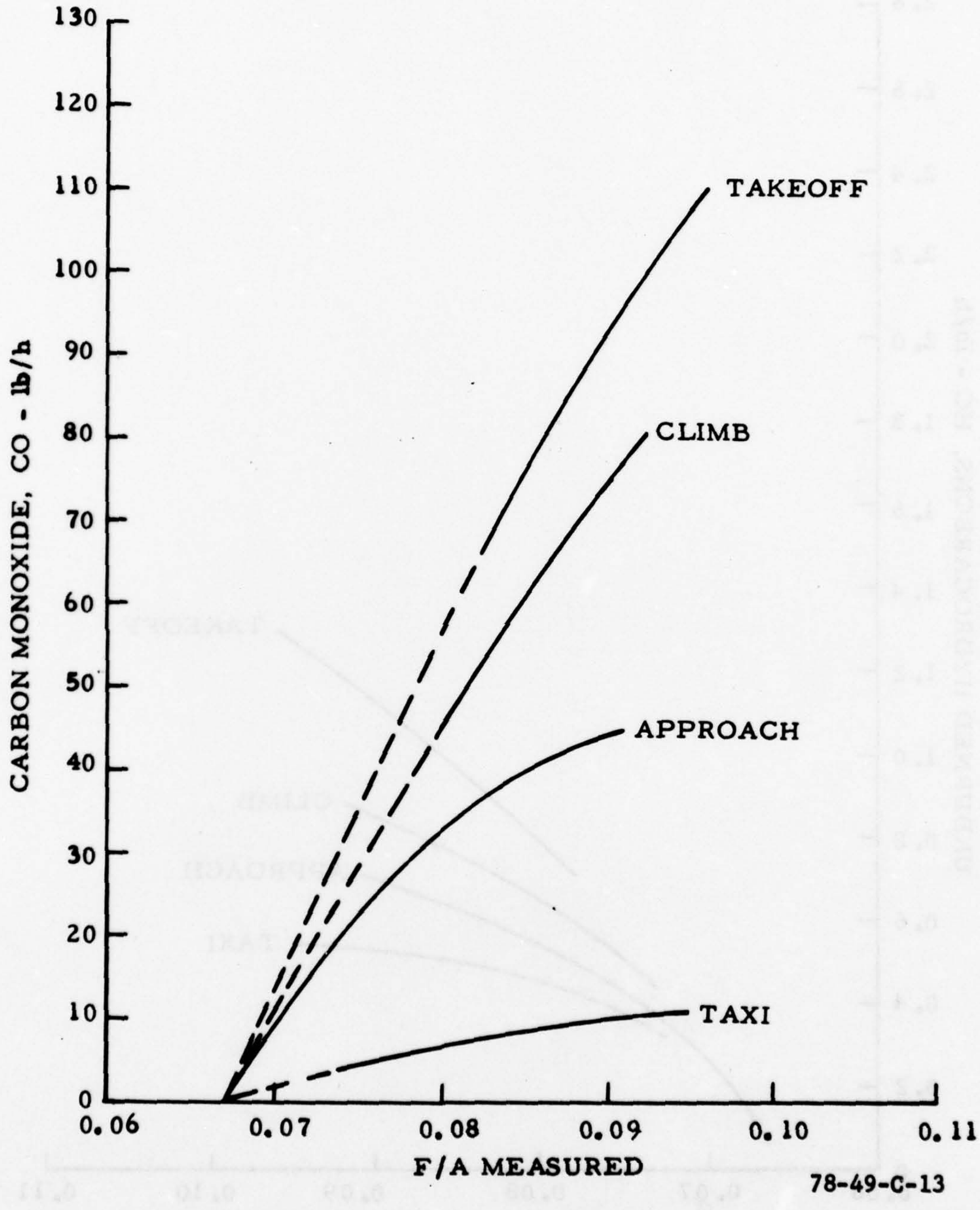

FIGURE C-13. SEA LEVEL STANDARD-DAY EMISSIONS CHARACTERISTICS FOR AN AVCO LYCOMING IO-360-A1B6D ENGINE--CARBON MONOXIDE

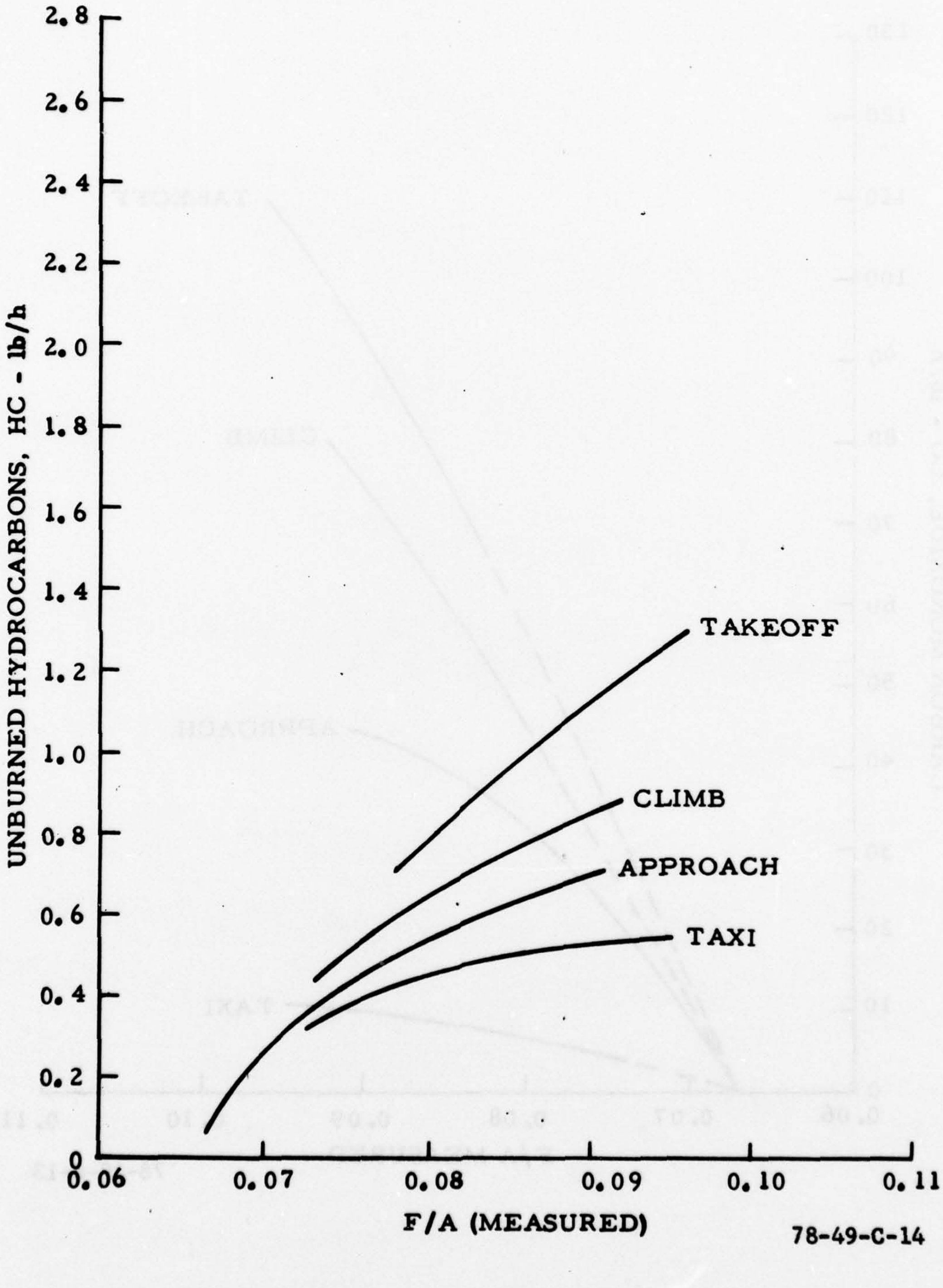

FIGURE C-14. SEA LEVEL STANDARD-DAY EMISSIONS CHARACTERISTICS FOR AN AVCO LYCOMING IO-360-A1B6D ENGINE--UNBURNED HYDROCARBONS (CH_4)

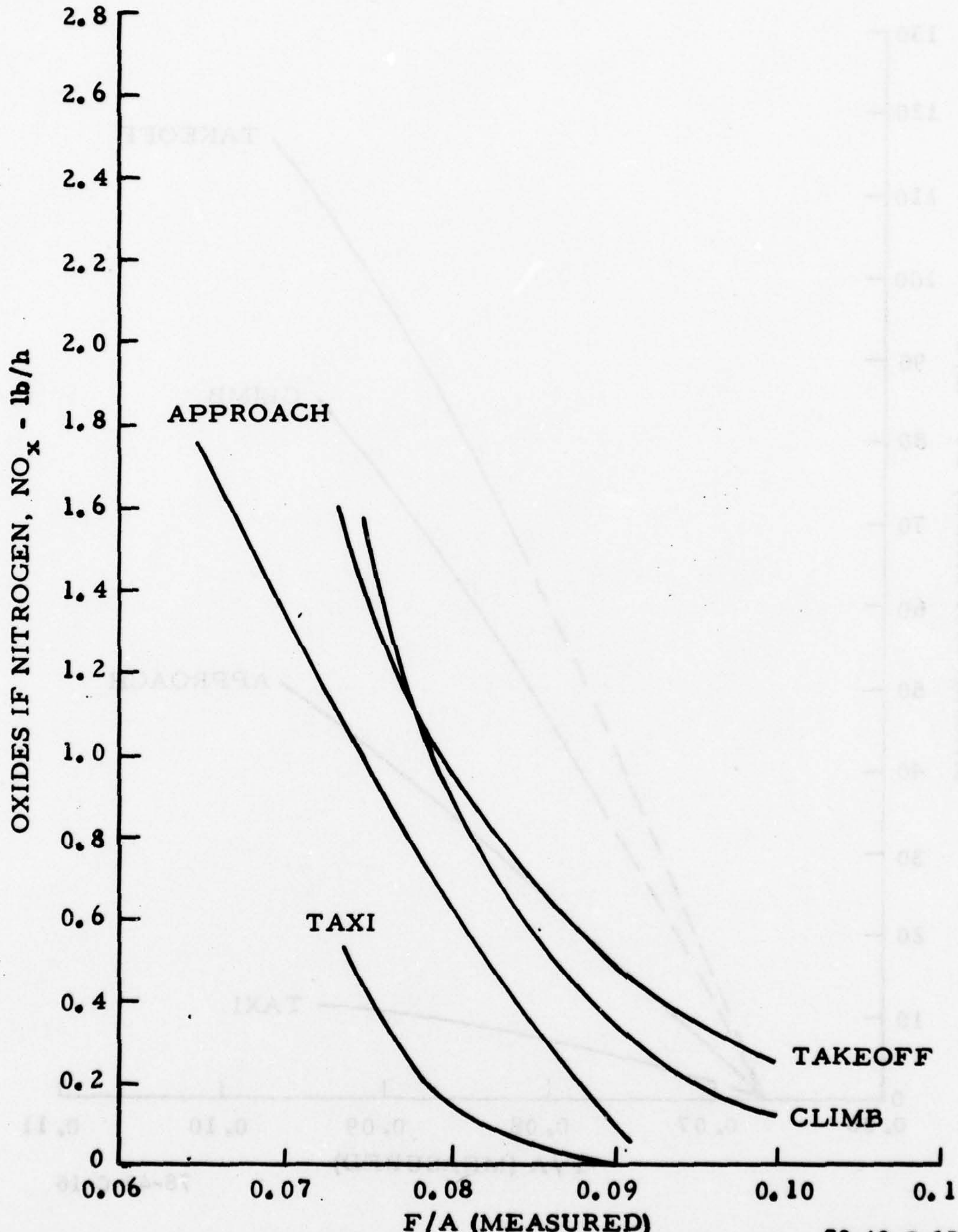

FIGURE C-15. SEA LEVEL STANDARD-DAY EMISSIONS CHARACTERISTICS FOR AN AVCO LYCOMING IO-360-A1B6D ENGINE--OXIDES OF NITROGEN (NO)

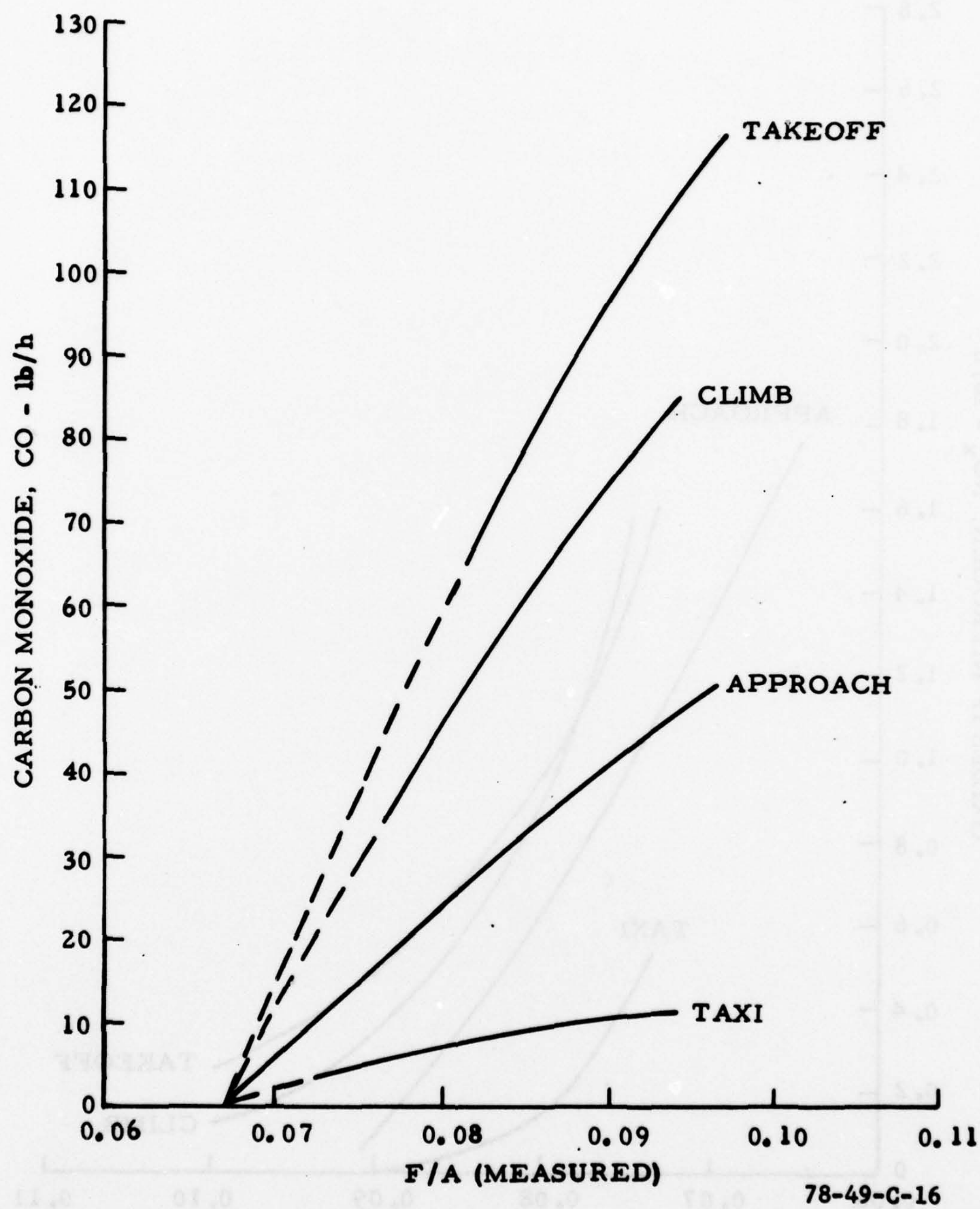

FIGURE C-16. SEA LEVEL HOT-DAY (T_1=95° F) EMISSIONS CHARACTERISTICS FOR AN AVCO LYCOMING IO-360-A1B6D ENGINE--CARBON MONOXIDE

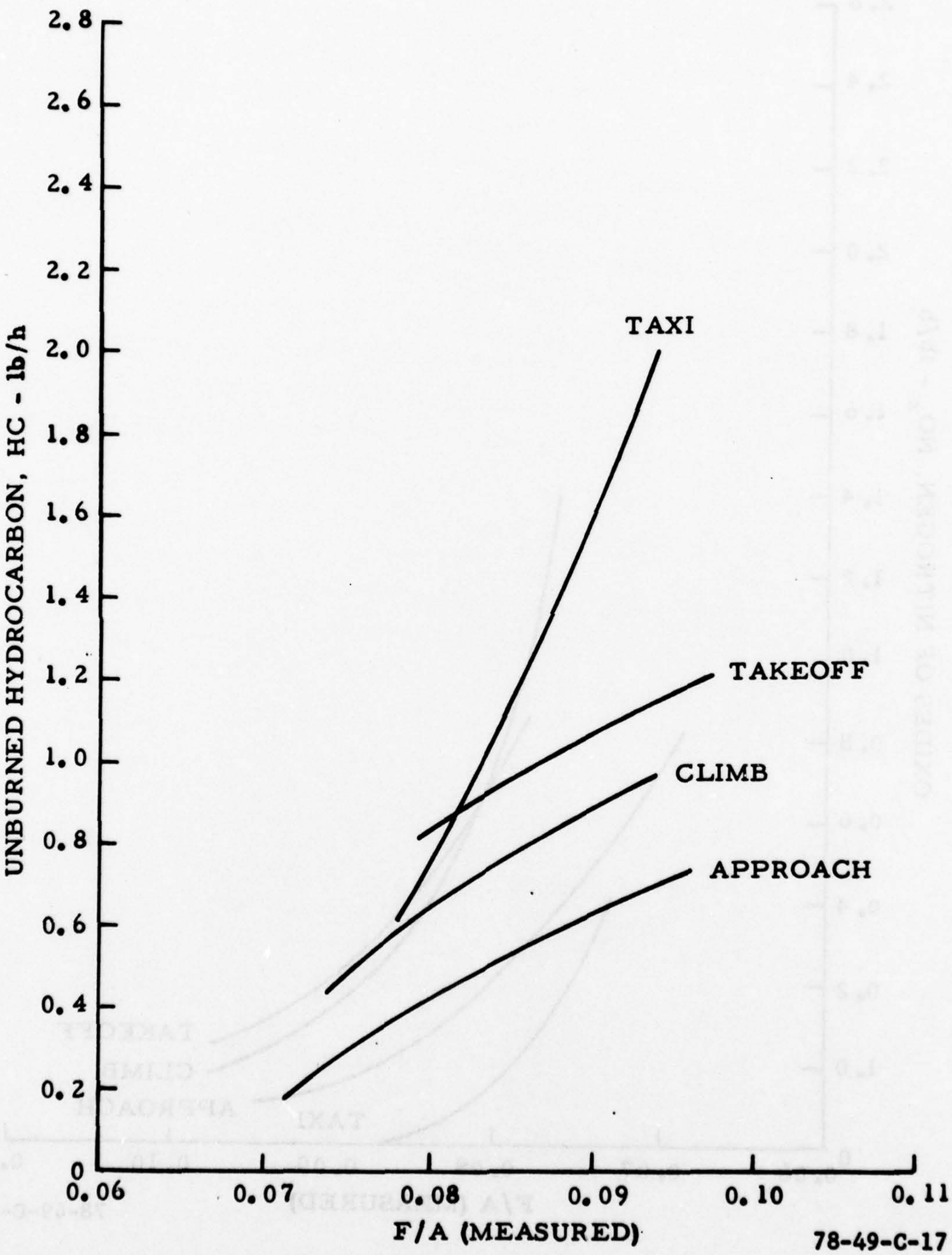

FIGURE C-17. SEA LEVEL HOT-DAY (T_i=95° F) EMISSIONS CHARACTERISTICS FOR AN AVCO LYCOMING IO-360-A1B6D ENGINE--UNBURNED HYDROCARBONS

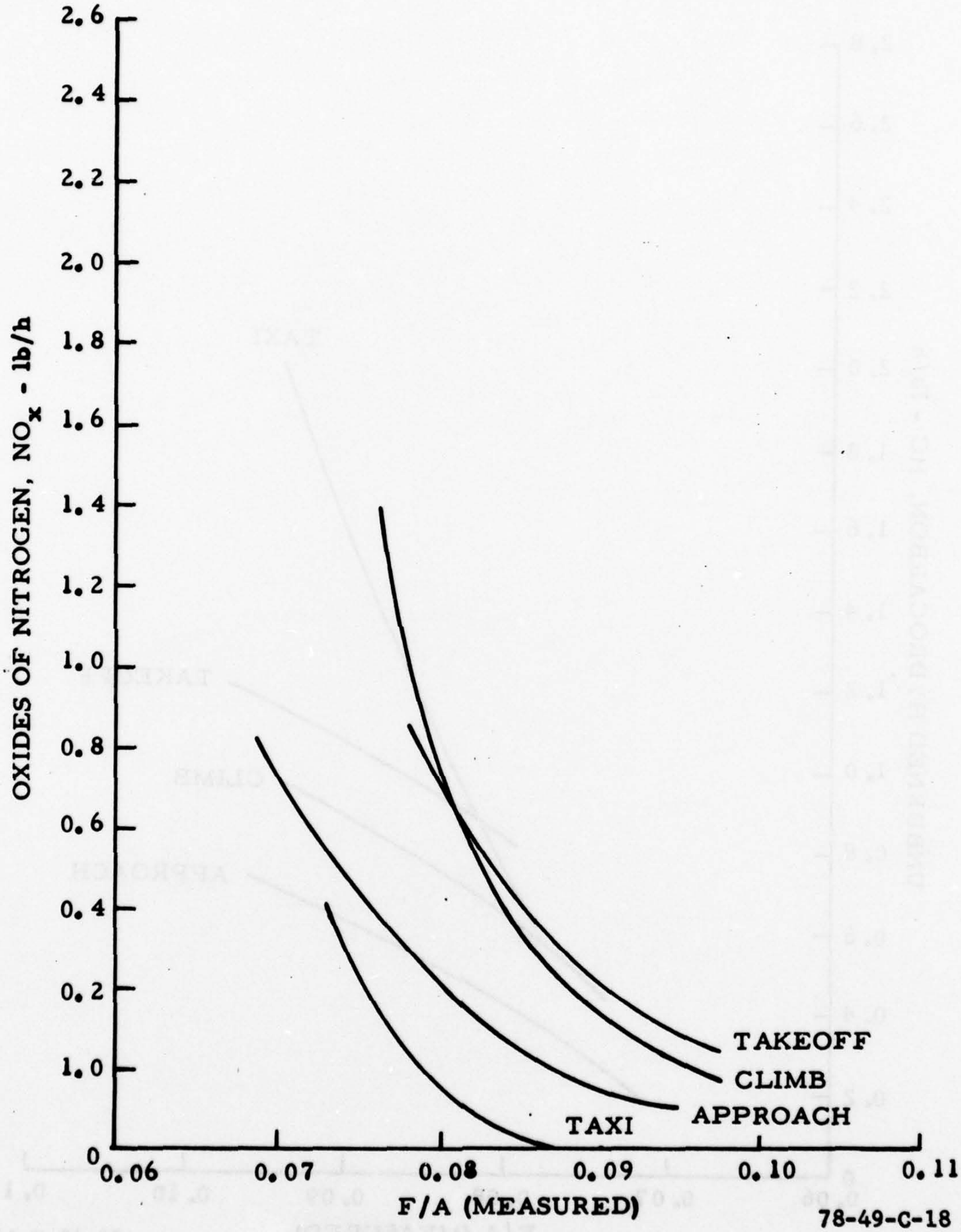

FIGURE C-18. SEA LEVEL HOT-DAY (T_1=95° F) EMISSIONS CHARACTERISTICS FOR AN AVCO LYCOMING IO-360-A1B6D ENGINE--OXIDES OF NITROGEN (NO)

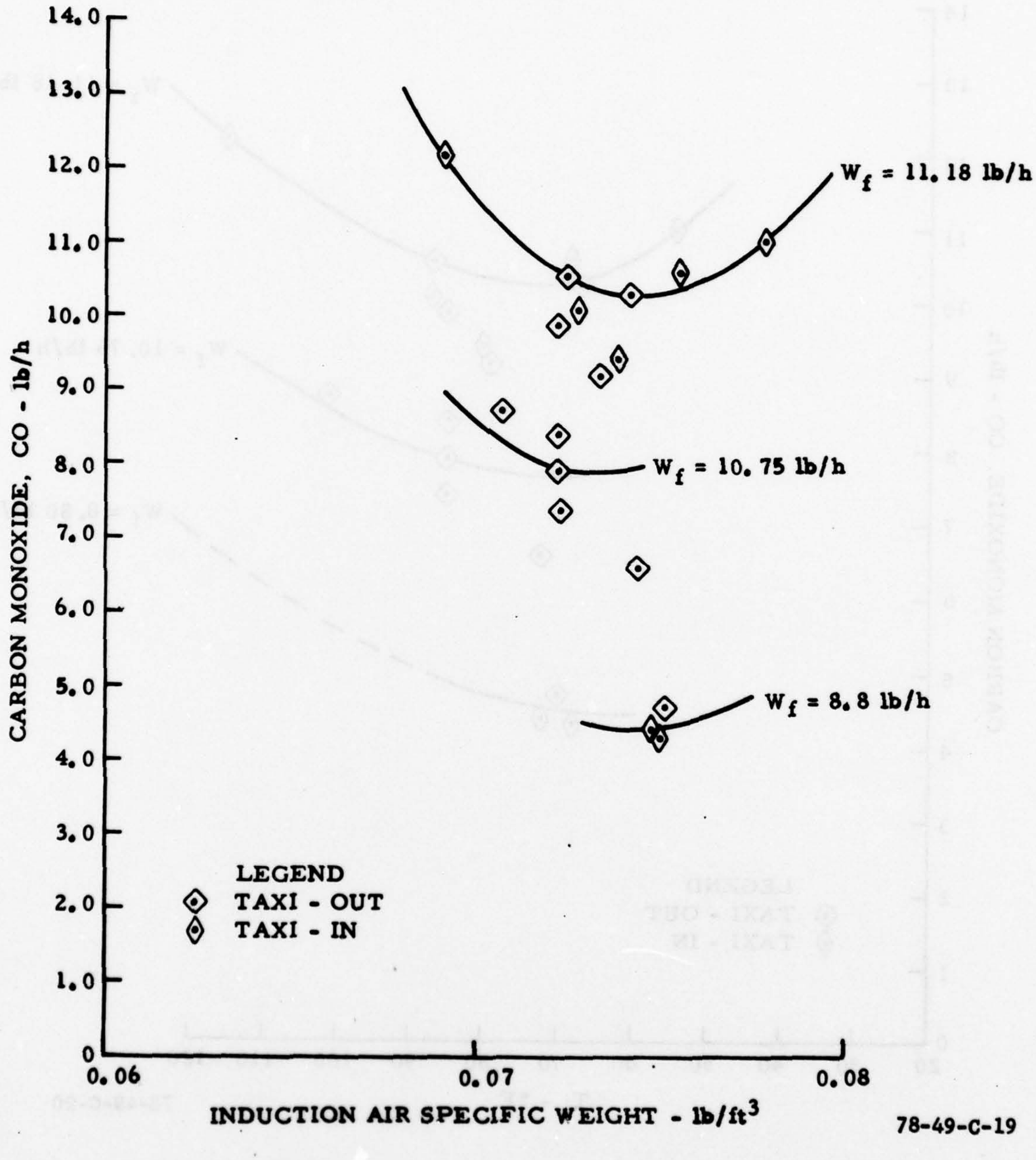

FIGURE C-19. TAXI MODE EMISSIONS CHARACTERISTICS FOR AN AVCO LYCOMING IO-360-A1B6D ENGINE AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT

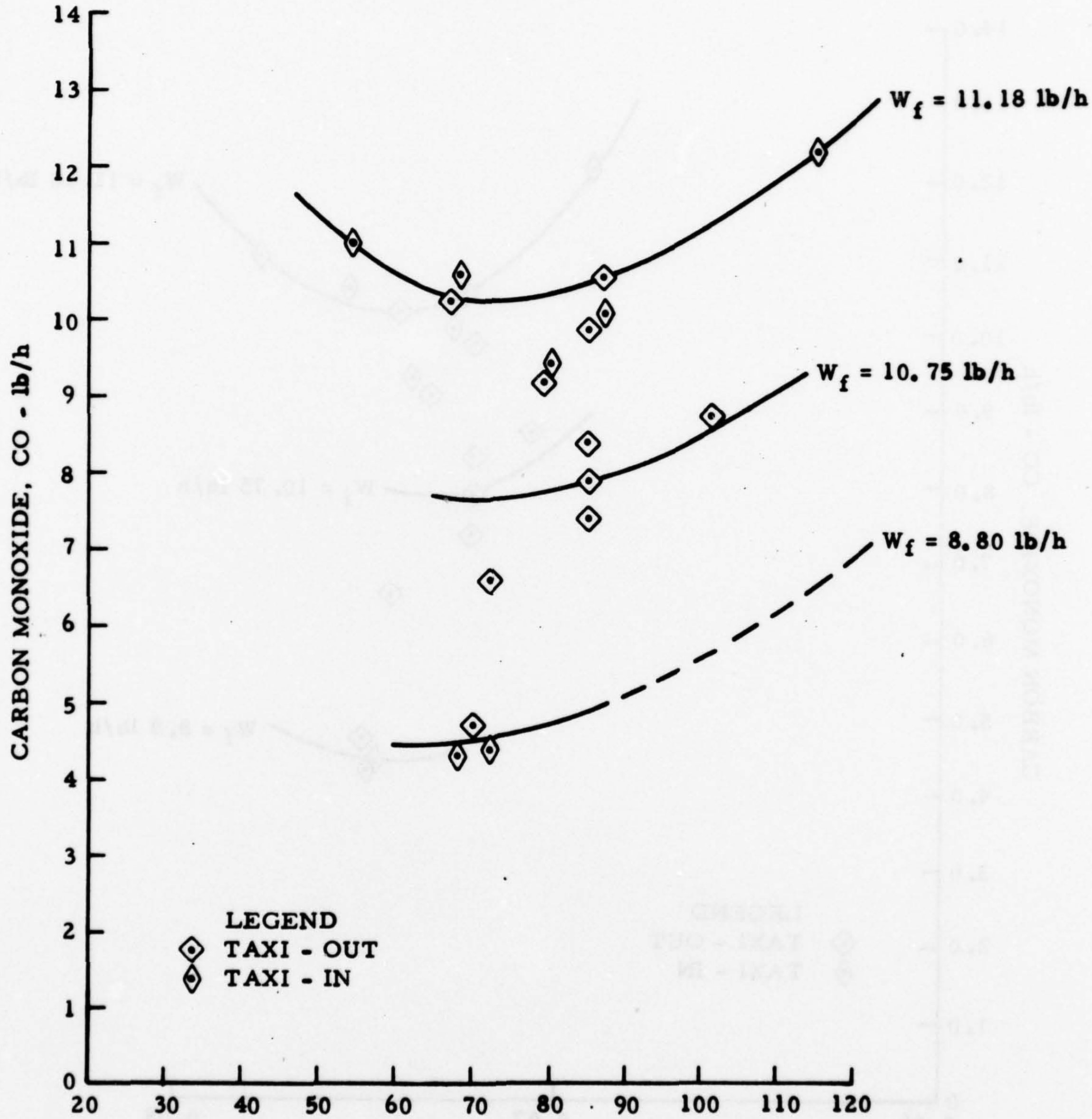

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FIGURE C-20. TAXI MODE EMISSIONS CHARACTERISTICS FOR AN AVCO LYCOMING IO-360-A1B6D ENGINE WITH VARYING AMBIENT (OR INDUCTION) AIR TEMPERATURES (CO)

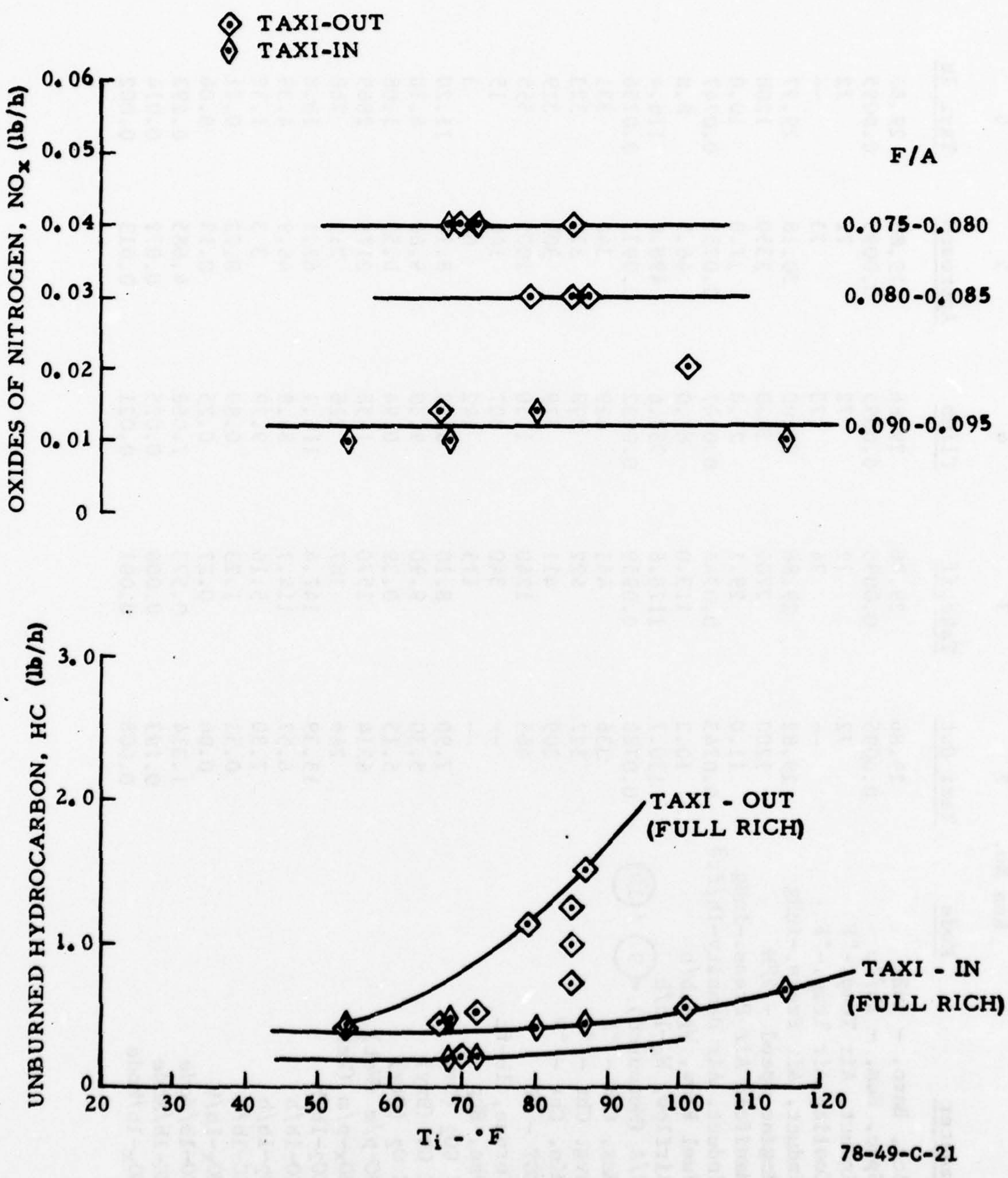

FIGURE C-21. TAXI MODE EMISSIONS CHARACTERISTICS FOR AN AVCO LYCOMING IO-360-A1B6D ENGINE WITH VARYING AMBIENT (OR INDUCTION) AIR TEMPERATURES (HC AND NO_x)

TABLE C-1. AVCO LYCOMING IO-360-A1B6D ENGINE NAFEC TEST DATA--BASELINE 1 (NO IDLE, FIVE-MODE) SPARK SETTING 25° BTC

Run No.		2	3	4	5	6
Parameter	**Mode**	**Taxi Out**	**Takeoff**	**Climb**	**Approach**	**Taxi In**
1. Act. Baro. - inHg		29.86	29.86	29.86	29.86	29.86
2. Spec. Hum. - lb/lb		0.0095	0.0095	0.0095	0.0095	0.0095
3. Induct. Air Temp.-°F		72	72	72	72	72
4. Cooling Air Temp.-°F		--	74	73	73	--
5. Induct. Air Press.-inHg		29.82	29.86	30.00	30.18	29.97
6. Engine Speed - RPM		1200	2700	2430	2350	1200
7. Manifold Air Press.-inHg		11.0	29.1	27.0	17.0	10.0
8. Induct. Air Density-lb/ft^3		0.0743	0.0744	0.0747	0.0752	0.0747
9. Fuel Flow, W_f-lb/h		10.2	113.0	87.0	46.5	8.8
10. Airflow, W_a-lb/h		130.7	1178.6	933.6	498.6	116.4
11. F/A (Measured) = 9 / 10		0.0780	0.0959	0.0932	0.0933	0.0756
12. Max. Cht - °F		336	441	429	346	331
13. Avg. Cht - °F		327	422	398	322	323
14. Min. Cht - °F		309	411	379	309	319
15. EGT - °F		465	1240	1150	1005	555
16. Torque, lb-ft		--	340	307	140	15
17. Obs. Bhp		--	175	142	63	3
18. % CO_2 (Dry)		7.90	8.10	8.10	8.10	11.20
19. % CO (Dry)		5.30	9.90	9.30	9.60	4.10
20. % O_2 (Dry)		5.15	0.39	0.94	0.59	1.08
21. HC-p/m (Wet)		6314	1570	1458	2179	2869
22. NO_x-p/m (Wet)		246	187	216	211	268
23. CO_2-lb/h		15.39	147.4	116.1	62.1	18.8
24. CO-lb/h		6.57	114.7	84.8	46.9	4.39
25. O_2-lb/h		7.30	5.16	9.79	3 3	1.32
26. HC-lb/h		0.51	1.23	0.89	0.72	0.21
27. NO_x-lb/h		0.04	0.27	0.25	0.13	0.04
28. CO-lb/Mode		1.314	0.573	7.068	4.685	0.293
29. HC-lb/Mode		0.103	0.006	0.075	0.072	0.014
30. NO_x-lb/Mode		0.008	0.001	0.021	0.013	0.002

TABLE C-2. AVCO LYCOMING IO-360-A1B6D ENGINE NAFEC TEST DATA--BASELINE 2--
RUN NOS. 29 THROUGH 33

Parameter	Run No. / Mode	29 Taxi Out	30 Takeoff	31 Climb	32 Approach	33 Taxi In
1.	Act. Baro. - inHg	29.86	29.86	29.86	29.86	29.86
2.	Spec. Hum. - lb/lb	0.0080	0.0080	0.0080	0.0080	0.0080
3.	Induct. Air Temp.-°F	87	87	87	87	87
4.	Cooling Air Temp.-°F	—	91	90	91	—
5.	Induct. Air Press.-inHg	29.85	29.84	30.00	30.17	29.95
6.	Engine Speed - RPM	1200	2700	2430	2350	1200
7.	Manifold Air Press.-inHg	11.5	29.1	27.0	17.0	10.0
8.	Induct. Air Density-lb/ft^3	0.0723	0.0723	0.0726	0.0731	0.0726
9.	Fuel Flow, W_f-lb/h	12.6	112.0	85.0	44.5	10.6
10.	Airflow, W_a-lb/h	133.8	1160.6	909.6	479.9	115.4
11.	F/A (Measured) = 9 / 10	0.0942	0.0965	0.0934	0.0927	0.0919
12.	Max. Cht - °F	333	447	437	368	323
13.	Avg. Cht - °F	330	428	410	340	315
14.	Min. Cht - °F	327	417	394	325	311
15.	EGT - °F	545	1258	1150	1010	554
16.	Torque, lb-ft	21	349	304	148	18
17.	Obs. Bhp	5	179	141	66	4
18.	% CO_2 (Dry)	6.96	8.23	8.23	8.29	8.33
19.	% CO (Dry)	7.94	9.83	9.14	9.39	8.98
20.	% O_2 (Dry)	5.30	0.62	1.15	0.87	0.61
21.	HC-p/m (Wet)	17117	1597	1559	1979	6025
22.	NO_x-p/m (Wet)	202	191	222	224	80
23.	CO_2-lb/h	14.50	148.2	115.2	61.4	14.66
24.	CO-lb/h	10.52	112.6	81.4	44.2	10.06
25.	O_2-lb/h	8.03	8.12	11.7	4.68	0.78
26.	HC-lb/h	1.51	1.23	0.93	0.62	0.45
27.	NO_x-lb/h	0.03	0.28	0.25	0.13	0.01
28.	CO-lb/Mode	2.105	0.563	6.785	4.424	0.671
29.	HC-lb/Mode	0.302	0.006	0.078	0.062	0.030
30.	NO_x-lb/Mode	0.007	0.001	0.021	0.013	0.001

TABLE C-3. AVCO LYCOMING IO-360-A1B6D ENGINE NAFEC TEST DATA--BASELINE 3--
RUN NOS. 137 THROUGH 141 (DRY BOTTLED AIR)

Parameter	Run No. / Mode	140 Taxi Out	141 Takeoff	142 Climb	143 Approach	144 Taxi In
1. Act. Baro. - inHg		30.07	30.07	30.07	30.07	30.07
2. Spec. Hum. - lb/lb		--	--	--	--	--
3. Induct. Air Temp.-°F		54	54	53	54	54
4. Cooling Air Temp.-°F		--	53	53	53	--
5. Induct. Air Press.-inHg		30.12	29.94	30.08	30.30	30.13
6. Engine Speed - RPM		1200	2700	2430	2300	1200
7. Manifold Air Press.-inHg		10.0	29.0	27.0	17.0	9.8
8. Induct. Air Density-lb/ft^3		0.0777	0.0772	0.0777	0.0781	0.0777
9. Fuel Flow, W_f-lb/h		11.6	115.0	89.0	45.5	10.6
10. Airflow, W_a-lb/h		122.0	1200.6	972.6	514.1	120.5
11. F/A (Measured) = 9 / 10		0.0951	0.0958	0.0915	0.0885	0.0880
12. Max. Cht - °F		335	445	429	332	306
13. Avg. Cht - °F		331	421	402	307	298
14. Min. Cht - °F		327	407	385	293	292
15. EGT - °F		509	1256	1157	950	518
16. Torque, lb-ft		30	369	330	156	33
17. Obs. Bhp		7	190	153	68	8
18. % CO_2 (Dry)		7.73	8.23	8.39	7.92	7.55
19. % CO (Dry)		9.26	9.24	8.45	9.01	9.41
20. % O_2 (Dry)		0.15	0.08	0.14	0.14	0.15
21. HC-p/m (Wet)		4983	1750	1433	2132	5642
22. NO_x-p/m (Wet)		82	204	259	216	68
23. CO_2-lb/h		14.40	152.6	123.3	61.9	13.90
24. CO-lb/h		10.98	108.3	79.0	44.8	11.02
25. O_2-lb/h		0.20	1.07	1.50	0.80	0.20
26. HC-lb/h		0.40	1.38	0.91	0.71	0.44
27. NO_x-lb/h		0.01	0.30	0.31	0.13	0.01
28. CO-lb/Mode		2.196	0.541	6.541	4.483	0.735
29. HC-lb/Mode		0.081	0.007	0.076	0.071	0.029
30. NO_x-lb/Mode		0.002	0.002	0.026	0.013	0.001

TABLE C-4. AVCO LYCOMING IO-360-A1B6D ENGINE NAFEC TEST DATA--BASELINE 4--RUN NOS. 909 THROUGH 913

Parameter	Mode / Run No.	909	910	911	912	913
		Taxi Out	Takeoff	Climb	Approach	Taxi In
1.	Act. Baro. - inHg	29.90	29.90	29.90	29.90	29.90
2.	Spec. Hum. - lb/ib	0.0075	0.0075	0.0075	0.0075	0.0075
3.	Induct. Air Temp.-°F	70	68	68	68	68
4.	Cooling Air Temp.-°F	--	69	70	69	--
5.	Induct. Air Press.-inHg	30.01	29.90	30.04	30.03	29.85
6.	Engine Speed - RPM	1200	2700	2430	2350	1200
7.	Manifold Air Press.-inHg	10.1	29.1	27.0	17.0	10.0
8.	Induct. Air Density-lb/ft^3	0.0750	0.0750	0.0754	0.0754	0.0749
9.	Fuel Flow, W_f-lb/h	8.7	113.0	88.0	46.5	8.8
10.	Airflow, W_a-lb/h	114.9	1189.5	945.8	513.8	114.5
11.	F/A (Measured) = 9 / 10	0.0757	0.0950	0.0930	0.0905	0.0769
12.	Max. Cht - °F	361	436	432	347	363
13.	Avg. Cht - °F	351	416	399	318	353
14.	Min. Cht - °F	338	406	380	304	347
15.	EGT - °F	554	1256	1157	1004	554
16.	Torque, lb-ft	26	375	--	--	--
17.	Obs. Bhp	6	193	--	--	--
18.	% CO_2 (Dry)	11.30	8.30	8.40	8.40	11.40
19.	% CO (Dry)	4.40	9.60	8.90	9.20	4.10
20.	% O_2 (Dry)	1.03	0.42	0.79	0.63	0.99
21.	HC-p/m (Wet)	2739	1579	1461	1940	2566
22.	NO_x-p/m (Wet)	296	206	245	240	316
23.	CO_2-lb/h	18.9	152.2	121 3	65.8	18.9
24.	CO-lb/h	4.7	112.0	81.8	45.9	4.3
25.	O_2-lb/h	1.3	5.60	8.30	3.6	1.2
26.	HC-lb/h	0.2	1.25	0.91	0.65	0.2
27.	NO_x-lb/h	0.04	0.30	0.29	0.15	0.04
28.	CO-lb/Mode	0.937	0.560	6.818	4.590	0.288
29.	HC-lb/Mode	0.039	0.006	0.076	0.065	0.012
30.	NO_x-lb/Mode	0.008	0.002	0.024	0.015	0.003

TABLE C-5. AVCO LYCOMING IO-360-A1B6D ENGINE NAFEC TEST DATA--BASELINE 5--
RUN NOS. 104 THROUGH 108 (HOT AIR)

	Run No.	104	105	106	107	108
Parameter	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
1. Act. Baro. - inHg		29.73	29.73	29.73	29.73	29.73
2. Spec. Hum. - lb/lb		0.0100	0.0100	0.0100	0.0100	0.0100
3. Induct. Air Temp.-°F		101	119	121	120	115
4. Cooling Air Temp.-°F		122	122	122	123	123
5. Induct. Air Press.-inHg		29.89	29.75	29.92	30148	29.92
6. Engine Speed - RPM		1200	2700	2430	2275	1200
7. Manifold Air Press.-inHg		10.5	29 2	27.0	17.0	10.5
8. Induct. Air Density-lb/ft^3		0.0706	0.0681	0.0682	0.0689	0.0690
9. Fuel Flow, W_f-lb/h		11 0	112.0	86.0	43.0	11.6
10. Airflow, W_a-lb/h		129.9	1146.2	929.9	471.6	123.5
11. F/A (Measured) = 9 / 10		0.0847	0.0977	0.0925	0.0912	0.0939
12. Max. Cht - °F		259	433	423	352	277
13. Avg. Cht - °F		247	419	402	330	265
14. Min. Cht - °F		241	413	388	318	260
15. EGT - °F		536	1220	1112	932	572
16. Torque, lb-ft		--	340	300	140	--
17. Obs. Bhp		--	175	139	61	--
18. % CO_2 (Dry)		8.66	7.65	7.73	7.43	7.52
19. % CO (Dry)		6.97	10.56	9.94	10.27	9.93
20. % O_2 (Dry)		2.95	0.76	1.19	1.28	1.58
21. HC-p/m (Wet)		6530	1799	1714	2431	8249
22. NO_x-p/m (Wet)		122	143	170	141	77
23. CO_2-lb/h		16.99	137.4	54.7	54.7	14.46
24. CO-lb/h		8.71	120.7	91.4	48.1	12.16
25. O_2-lb/h		4.21	9.93	6.74	6.85	2.21
26. HC-lb/h		0.54	1.38	1.05	0.75	0.67
27. NO_x-lb/h		0.02	0.20	0.19	0.08	0.01
28. CO-lb/Mode		1.741	0.604	7.617	4.609	0.810
29. HC-lb/Mode		0.108	0.007	0.087	0.075	0.045
30. NO_x-lb/Mode		0.004	0.001	0.016	0.008	0.001

TABLE C-6. AVCO LYCOMING IO-360-A1B6D ENGINE NAFEC TEST DATA--BASELINE 6--
RUN NOS. 923 THROUGH 927

Parameter	Run No. / Mode	923 Taxi Out	924 Takeoff	925 Climb	926 Approach	927 Taxi In
1. Act. Baro. - inHg		29.91	29.91	29.91	29.91	29.91
2. Spec. Hum. - lb/lb		0.0075	0.0075	0.0075	0.0075	0.0075
3. Induct. Air Temp.-°F		79	79	80	80	80
4. Cooling Air Temp.-°F		119	79	80	81	108
5. Induct. Air Press.-inHg		29.79	29.90	30.05	30.22	30.01
6. Engine Speed - RPM		1200	2700	2430	2350	1200
7. Manifold Air Press.-inHg		11.4	29.0	27.0	17.0	10.1
8. Induct. Air Density-lb/ft^3		0.0732	0.0735	0.0737	0.0742	0.0737
9. Fuel Flow, W_f-lb/h		11.95	113.0	87.0	45 5	10.60
10. Airflow, W_a-lb/h		134.2	1169.0	927.4	518.1	114.8
11. F/A (Measured) = 9 / 10		0.0890	0.0967	0.0938	0.0878	0.0923
12. Max. Cht - °F		357	414	428	365	333
13. Avg. Cht - °F		343	399	400	336	322
14. Min. Cht - °F		327	392	380	322	313
15. EGT - °F		536	1238	1148	1004	545
16. Torque, lb-ft		20	357	312	151	28
17. Obs. Bhp		5	184	144	68	6
18. % CO_2 (Dry)		7.34	8.24	8.29	8.26	8.71
19. % CO (Dry)		7.11	9.71	9.07	9.38	8.44
20. % O_2 (Dry)		3.89	0.61	1.09	0.85	1.11
21. HC-p/m (Wet)		12,735	1679	1517	2040	5264
22. NO_x-p/m (Wet)		186	193	229	228	101
23. CO_2-lb/h		14.88	149.1	118.2	66.0	15.26
24. CO-lb/h		9.17	111.9	82.3	47.7	9.41
25. O_2-lb/h		5.73	8.03	11.3	4.94	1.41
26. HC-lb/h		1.13	1.31	0.93	0.68	0.40
27. NO_x-lb/h		0.03	0.28	0.26	0.14	0.014
28. CO-lb/Mode		1.835	0.559	6.858	4.769	0.627
29. HC-lb/Mode		0.226	0.007	0.077	0.068	0.0265
30. NO_x-lb/Mode		0.006	0.001	0.022	0.014	0.001

TABLE C-7. AVCO LYCOMING IO-360-A1B6D ENGINE NAFEC TEST DATA--TAKEOFF--T.O. MODE--RUN NOS. 16 THROUGH 19

Parameter	Run No. Mode	16 Takeoff	17 Takeoff	18 Takeoff	19 Takeoff
1. Act. Baro. - inHg		29.91	29.91	29.91	29.91
2. Spec. Hum. - lb/lb		0.0080	0.0080	0.0080	0.0080
3. Induct. Air Temp.-°F		81	81	81	81
4. Cooling Air Temp.-°F		81	81	82	82
5. Induct. Air Press.-inHg		29.90	29.90	29.90	29.91
6. Engine Speed - RPM		2700	2700	2700	2700
7. Manifold Air Press.-inHg		29.1	29.1	29.1	29.1
8. Induct. Air Density-lb/ft^3		0.0732	0.0732	0.0732	0.0733
9. Fuel Flow, W_f-lb/h		113.0	108.0	103.0	98.0
10. Airflow, W_a-lb/h		1175.1	1169.1	1181.2	1163.7
11. F/A (Measured) = 9 / 10		0.0962	0.0924	0.0872	0.0842
12. Max. Cht - °F		441	452	462	471
13. Avg. Cht - °F		423	432	442	451
14. Min. Cht - °F		413	423	431	442
15. EGT - °F		1256	1285	1310	1335
16. Torque, lb-ft		352	354	353	354
17. Obs. Bhp		181	182	181.5	182
18. % CO_2 (Dry)		8.20	8.81	9.44	10.12
19. % CO (Dry)		9 80	8.74	7.93	6.76
20. % O_2 (Dry)		0.65	0.68	0.53	0.59
21. HC-p/m (Wet)		1646	1406	1436	1288
22. NO_x-p/m (Wet)		191	267	365	534
23. CO_2-lb/h		149.4	157.3	168.5	175.4
24. CO-lb/h		113.6	99.3	90.1	74.6
25. O_2-lb/h		8.61	8.83	6.88	7.44
26. HC-lb/h		1.29	1.08	1.09	0.95
27. NO_x-lb/h		0.28	0.38	0.52	0.74
28. CO-lb/Mode		0.568	0.497	0.450	0.373
29. HC-lb/Mode		0.006	0.005	0.005	0.005
30. NO_x-lb/Mode		0.001	0.002	0.003	0.004

TABLE C-8. AVCO LYCOMING IO-360-A1B6D ENGINE NAFEC TEST DATA--T.O. MODE--RUN NOS. 167 THROUGH 174 (AMBIENT AND DRY BOTTLED AIR)

Parameter	Run No. / Mode	167 Takeoff	168 Takeoff	169 Takeoff	170 Takeoff	171 Takeoff	172 Takeoff	173 Takeoff	174 Takeoff
1. Act. Baro. - inHg		30.05	30.05	30.05	30.05	30.05	30.05	30.05	30.05
2. Spec. Hum. - lb/lb		0.0010	--	0.0010	--	0.0010	--	0.0010	--
3. Induct. Air Temp.-°F		56	53	55	52	55	51	55	52
4. Cooling Air Temp.-°F		53	53	53	53	53	53	53	53
5. Induct. Air Press.-inHg		30.02	29.92	30.04	29.92	30.04	29.94	30.04	29.94
6. Engine Speed - RPM		2700	2700	2700	2700	2700	2700	2700	2700
7. Manifold Air Press.-inHg		19.0	19.0	29.0	29.0	29.0	29.0	29.0	29.0
8. Induct. Air Density-lb/ft^3		0.0771	0.0773	0.0773	0.0774	0.0773	0.0776	0.0773	0.0775
9. Fuel Flow, W_f-lb/h		115.0	115.0	110.0	110.0	105.0	105.0	100.0	100.0
10. Airflow, W_a-lb/h		1206.0	1201.3	1207.6	1212.1	1202.6	1209.9	1207.6	1194.1
11. F/A (Measured) = 9 / 10		0.0954	0.0957	0.0911	0.0908	0.0873	0.0868	0.0828	0.0837
12. Max. Cht - °F		440	445	455	456	467	468	475	478
13. Avg. Cht - °F		416	420	432	432	441	442	450	453
14. Min. Cht - °F		401	405	416	416	425	427	438	440
15. EGT - °F		1238	1256	1274	1274	1321	1321	1335	1335
16. Torque, lb-ft		376	373	377	372	375	374	375	374
17. Obs. Bhp		193	192	194	191	193	192	193	192
18. % CO_2 (Dry)		7.67	7.57	8.42	8.31	9.16	9.02	9.93	9.76
19. % CO (Dry)		9.33	9.36	8.17	8.22	6.99	7.09	5.88	5.98
20. % O_2 (Dry)		0.83	0.82	0.90	0.81	0.91	0.80	0.80	0.74
21. HC-p/m (Wet)		1719	1695	1515	1523	1358	1389	1240	1285
22. NO_x-p/m (Wet)		209	203	313	303	469	449	688	662
23. CO_2-lb/h		142.2	139.7	154.2	152.7	164.7	163.1	176.9	172.0
24. CO-lb/h		110.1	110.0	95.2	96.1	80.0	81.6	66.7	67.1
25. O_2-lb/h		11.2	11.0	12.0	10.8	11.9	10.5	10.4	9.48
26. HC-lb/h		1.37	1.35	1.19	1.20	1.05	1.08	0.95	0.98
27. NO_x-lb/h		0.31	0.30	0.46	0.45	0.68	0.65	0.98	0.94
28. CO-lb/Mode		0.551	0.550	0.476	0.481	0.400	0.408	0.333	0.335
29. HC-lb/Mode		0.007	0.007	0.006	0.006	0.005	0.005	0.005	0.005
30. NO_x-lb/Mode		0.002	0.002	0.002	0.002	0.003	0.003	0.005	0.005

TABLE C-9. AVCO LYCOMING IO-360-A1B6D ENGINE NAFEC TEST DATA--CLIMB MODE--RUN NOS. 20 THROUGH 23

Parameter	Run No.	20	20	20	23
	Mode	Climb	Climb	Climb	Climb
1. Act. Baro. - inHg		29.86	29.86	29.86	29.86
2. Spec. Hum. - lb/lb		0.0080	0.0080	0.0080	0.0080
3. Induct. Air Temp.-°F		87	87	87	87
4. Cooling Air Temp.-°F		89	90	90	90
5. Induct. Air Press.-inHg		29.99	29.99	29.99	29.99
6. Engine Speed - RPM		2430	2430	2430	2430
7. Manifold Air Press.-inHg		27.0	27.0	27.0	27.0
8. Induct. Air Density-lb/ft^3		0.0727	0.0727	0.0727	0.0727
9. Fuel Flow, W_f-lb/h		86.0	81.0	76.0	71.0
10. Airflow, W_a-lb/h		921.1	921.1	721.1	918.0
11. F/A (Measured) = 9 / 10		0.0934	0.0879	0.0825	0.0773
12. Max. Cht - °F		411	417	427	433
13. Avg. Cht - °F		388	392	401	409
14. Min. Cht - °F		374	375	384	392
15. EGT - °F		1150	1170	1200	1240
16. Torque, lb-ft		306	309	308	310
17. Obs. Bhp		142	143	143	143
18. % CO_2 (Dry)		8.04	9.28	10.12	11.11
19. % CO (Dry)		9.21	7.58	6.00	4.14
20. % O_2 (Dry)		1.10	1.30	1.45	1.80
21. HC-p/m (Wet)		1576	1324	1160	924
22. NO_x-p/m (Wet)		217	363	636	1192
23. CO_2-lb/h		113.8	129.2	138.4	148.8
24. CO-lb/h		83.0	67.2	52.2	35.3
25. O_2-lb/h		11.3	13.2	14.4	17.5
26. HC-lb/h		0.96	0.79	0.68	0.53
27. NO_x-lb/h		0.25	0.40	0.69	1.27
28. CO-lb/Mode		6.913	5.599	4.352	2.941
29. HC-lb/Mode		0.080	0.066	0.056	0.044
30. NO_x-lb/Mode		0.021	0.034	0.058	0.106

TABLE C-10. AVCO LYCOMING IO-360-A1B6D ENGINE NAFEC TEST DATA--CLIMB MODE--RUN NOS. 159 THROUGH 166 (AMBIENT AND DRY BOTTLES AIR)

Parameter — Run No. / Mode	159 Climb	160 Climb	161 Climb	162 Climb	163 Climb	164 Climb	165 Climb	166 Climb
1. Act. Baro. - inHg	30.04	30.04	30.04	30.04	30.04	30.04	30.04	30.05
2. Spec. Hum. - lb/lb	0.0035	—	0.0035	—	0.0035	—	0.0035	0.0030
3. Induct. Air Temp.-°F	57	58	56	55	56	54	56	52
4. Cooling Air Temp.-°F	53	53	52	53	53	53	53	53
5. Induct. Air Press.-inHg	30.16	30.08	30.16	30.08	30.16	30.08	30.16	30.09
6. Engine Speed - RPM	2430	2430	2430	2430	2430	2430	2430	2430
7. Manifold Air Press.-inHg	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0
8. Induct. Air Density-lb/ft^3	0.0773	0.0770	0.0775	0.0774	0.0775	0.0776	0.0775	0.0779
9. Fuel Flow, W_f-lb/h	89.0	89.0	84.0	84.0	79.0	79.0	74.0	74.0
10. Airflow, W_a-lb/h	977.8	966.7	979.1	950.4	979.1	961.1	979.1	958.2
11. F/A (Measured) = 9 / 10	0.0910	0.0921	0.0858	0.0884	0.0807	0.0822	0.0756	0.0772
12. Max. Cht - °F	417	414	424	423	432	433	439	440
13. Avg. Cht °F	393	392	400	400	409	410	416	417
14. Min. Cht - °F	374	375	384	384	393	392	400	401
15. EGT - °F	1157	1157	1184	1184	1211	1211	1238	1238
16. Torque, lb-ft	336	334	336	336	338	337	339	338
17. Obs. Bhp	155.5	154.5	155.5	155.5	156.4	155.9	156.8	156.4
18. % CO_2 (Dry)	8.08	7.95	8.83	8.71	9.76	9.63	10.58	10.43
19. % CO (Dry)	8.18	8.27	6.89	6.98	5.34	5.31	3.77	3.86
20. % O_2 (Dry)	1.54	1.52	1.62	1.55	1.81	1.77	2.08	2.01
21. HC-p/m (Wet)	1359	1437	1262	1264	1047	1053	884	894
22. NO_x-p/m (Wet)	279	270	442	421	745	735	1287	1233
23. CO_2-lb/h	120.0	117.1	129.3	124.2	140.7	136.4	150.5	145.0
24. CO-lb/h	77.3	77.5	64.2	63.3	49.0	47.9	34.1	34.2
25. O_2-lb/h	16.6	16.3	17.2	16.1	19.0	18.2	21.5	20.3
26. HC-lb/h	0.87	0.91	0.79	0.78	0.65	0.64	0.53	0.53
27. NO_x-lb/h	0.33	0.32	0.52	0.48	0.86	0.84	1.45	1.37
28. CO-lb/Mode	6.443	6.461	5.354	5.277	4.083	3.990	2.844	2.847
29. HC-lb/Mode	0.072	0.076	0.066	0.065	0.054	0.053	0.044	0.044
30. NO_x-lb/Mode	0.028	0.027	0.043	0.040	0.072	0.070	0.121	0.114

TABLE C-11. AVCO LYCOMING IO-360-A1B6D ENGINE NAFEC TEST DATA--CLIMB MODE--RUN NOS. 122 THROUGH 125 (SEA LEVEL HOT DAY)

Parameter	Run No. / Mode	122 Climb	123 Climb	124 Climb	125 Climb
1. Act. Baro. - inHg		29.60	29.60	29.60	29.60
2. Spec. Hum. - lb/lb		0.0110	0.0110	0.0110	0.0110
3. Induct. Air Temp.-°F		109	113	115	117
4. Cooling Air Temp.-°F		116	116	117	118
5. Induct. Air Press.-inHg		29.80	29.81	29.82	29.81
6. Engine Speed - RPM		2430	2430	2430	2430
7. Manifold Air Press.-inHg		27.0	27.0	27.0	27.0
8. Induct. Air Density-lb/ft^3		0.0694	0.0689	0.0687	0.0685
9. Fuel Flow, W_f-lb/h		87.0	82.0	77.0	72.0
10. Airflow, W_a-lb/h		917.7	911.5	910.2	911.8
11. F/A (Measured) = 9 / 10		0.0948	0.0900	0.0846	0.0790
12. Max. Cht - °F		410	428	443	453
13. Avg. Cht - °F		389	406	421	431
14. Min. Cht - °F		374	388	405	415
15. EGT - °F		1121	1139	1166	1193
16. Torque, lb-ft		300	301	302	302
17. Obs. Bhp		138.8	139.3	139.7	139.7
18. % CO_2 (Dry)		7.83	8.37	9.33	10.04
19. % CO (Dry)		9.71	8.68	6.93	5.65
20. % O_2 (Dry)		1.28	1.33	1.54	1.61
21. HC-p/m (Wet)		1750	1576	1315	1111
22. NO_x-p/m (Wet)		167	232	430	671

TABLE C-12. AVCO LYCOMING IO-360-A1B60 ENGINE NAFEC TEST DATA--APPROACH MODE--RUN NOS. 24 THROUGH 27

Parameter	Run No. / Mode	24 Approach	25 Approach	26 Approach	27 Approach
1.	Act. Baro. - inHg	29.85	29.85	29.85	29.85
2.	Spec. Hum. - lb/lb	0.0080	0.0080	0.0080	0.0080
3.	Induct. Air Temp.-°F	88	88	88	88
4.	Cooling Air Temp.-°F	91	91	91	91
5.	Induct. Air Press.-inHg	30.15	30.16	30.16	30.16
6.	Engine Speed - RPM	2350	2350	2350	2280
7.	Manifold Air Press.-inHg	17.0	17.0	17.0	17.0
8.	Induct. Air Density-lb/ft^3	0.0729	0.0729	0.0729	0.0729
9.	Fuel Flow, W_f-lb/h	45.0	40.0	35.0	30.0
10.	Airflow, W_a-lb/h	493.8	490.9	490.9	476.3
11.	F/A (Measured) = 9 / 10	0.0911	0.0815	0.0713	0.0630
12.	Max. Cht - °F	342	347	353	326
13.	Avg. Cht - °F	317	322	331	318
14.	Min. Cht - °F	305	311	323	300
15.	EGT - °F	1005	1050	1130	1060
16.	Torque, lb-ft	151	152	151	137
17.	Obs. Bhp	68	68	68	59.5
18.	% CO_2 (Dry)	8.38	10.32	12.64	12.39
19.	% CO (Dry)	9.26	6.13	2.15	0.65
20.	% O_2 (Dry)	0.86	0.92	1.24	3.03
21.	HC-p/m (Wet)	2004	1427	875	468
22.	NO_x-p/m (Wet)	236	714	1784	1733
23.	CO_2-lb/h	63.7	75.1	88.6	83.8
24.	CO-lb/h	44.8	28.4	9.60	2.80
25.	O_2-lb/h	4.75	4.87	6.32	14.91
26.	HC-lb/h	0.65	0.44	0.26	0.13
27.	NO_x-lb/h	0.14	0.41	0.995	0.92
28.	CO-lb/Mode	4.480	2.838	0.960	0.280
29.	HC-lb/Mode	0.065	0.044	0.026	0.013
30.	NO_x-lb/Mode	0.014	0.041	0.0995	0.092

TABLE C-13. AVCO LYCOMING IO-360-A1B6D ENGINE NAFEC TEST DATA --APPROACH MODE-- RUN NOS. 151 THROUGH 158

	Run No.	151	152	153	154	155	156	157
Parameter	**Mode**	**Approach**	**Approach**	**Approach**	**Approach**	**Approach**	**Approach**	**Approach**
1. Act. Baro. - inHg		30.34	30.34	30.34	30.34	30.34	30.34	30.34
2. Spec. Hum. - lb/lb		0.0040	0.0040	0.0040	0.0040	0.0040	0.0040	0.0040
3. Induct. Air Temp.-°F		57	58	57	58	56	58	57
4. Cooling Air Temp.-°F		57	57	56	56	57	57	57
5. Induct. Air Press.-inHg		30.60	30.44	30.59	30.44	30.44	30.465	30.60
6. Engine Speed - RPM		2350	2350	2350	2350	2350	2350	2275
7. Manifold Air Press.-inHg		17.0	16.9	17.0	17.0	17.1	17.1	17.1
8. Induct. Air Density-lb/ft^3		0.0784	0.0779	0.0784	0.0779	0.0782	0.0779	0.0784
9. Fuel Flow, W_f-lb/h		45.5	46.5	41.5	41.5	36.5	36.0	31.5
10. Airflow, W_a-lb/h		543.9	544.9	565.9	536.5	565.1	564.1	532.5
11. F/A (Measured) = 9 / 10		0.0837	0.0853	0.0733	0.0774	0.0646	0.0638	0.0592
12. Max. Cht - °F		350	347	352	352	345	346	313
13. Avg. Cht - °F		319	315	325	326	326	328	303
14. Min. Cht - °F		304	300	312	314	311	311	283
15. EGT °F		1031	1031	1067	1076	1112	1094	1040
16. Torque, lb-ft		166	170	175	174	171	162	151
17. Obs. Bhp		74.3	76.1	78.3	77.9	76.5	72.5	65.4
18. % CO_2 (Dry)		9.32	9.34	11.37	11.38	12.95	12.77	11.66
19. % CO (Dry)		7.39	7.38	4.11	4.17	0.86	0.83	0.06
20. % O_2 (Dry)		1.39	1.31	1.72	1.57	2.65	2.75	4.85
21. HC-p/m (Wet)		1862	1907	1532	1521	757	720	316
22. NO_x-p/m (Wet)		413	425	1740 (EST)	1740 (EST)	3074	3044	2161
23. CO_2-lb/h		76.8	77.3	94.4	89.9	104.9	103.5	88.8
24. CO-lb/h		38.8	38.9	21.7	21.0	4.43	4.28	0.29
25. O_2-lb/h		8.33	7.89	10.38	9.02	15.61	16.20	26.9
26. HC-lb/h		0.64	0.66	0.53	0.51	0.25	0.24	0.10
27. NO_x-lb/h		0.27	0.28	1.13	1.09	1.93	1.91	1.27
28. CO-lb/Mode		3.875	3.889	2.172	2.096	0.443	0.428	0.029
29. HC-lb/Mode		0.064	0.066	0.053	0.051	0.025	0.024	0.010
30. NO_x-lb/Mode		0.027	0.028	0.113	0.109	0.193	0.191	0.127

TABLE C-14. AVCO LYCOMING IO-360-A1B6D ENGINE NAFEC TEST DATA--TAXI MODE--RUN NOS. 12 THROUGH 15

Parameter	Run No.	12	13	14	15
	Mode	Taxi	Taxi	Taxi	Taxi
1. Act. Baro. - inHg		29.86	29.86	29.86	29.86
2. Spec. Hum. - lb/lb		0.0085	0.0085	0.0085	0.0085
3. Induct. Air Temp.-°F		85	85	85	85
4. Cooling Air Temp.-°F		128	125	122	131
5. Induct. Air Press.-inHg		29.68	29.66	29.65	29.66
6. Engine Speed - RPM		1200	1200	1200	1200
7. Manifold Air Press.-inHg		12.0	12.0	11.9	11.9
8. Induct. Air Density-lb/ft^3		0.0722	0.0721	0.0721	0.0721
9. Fuel Flow, W_f-lb/h		10.6	11.2	11.6	11.8
10. Airflow, W_a-lb/h		132.7	132.9	134.3	132.9
11. F/A (Measured) = 9 / 10		0.0799	0.0843	0.0864	0.0888
12. Max. Cht - °F		376	370	373	363
13. Avg. Cht - °F		358	354	356	351
14. Min. Cht - °F		340	337	341	342
15. EGT - °F		500	509	527	536
16. Torque, lb-ft		18	20	21	23
17. Obs. Bhp		4	5	5	5
18. % CO_2 (Dry)		7.00	6.73	7.19	6.12
19. % CO (Dry)		5.77	6.18	7.47	6.60
20. % O_2 (Dry)		6.44	5.98	5.29	5.39
21. HC-p/m (Wet)		8713	11472	11520	14390
22. NO_x-p/m (Wet)		277	214	212	191
23. CO_2-lb/h		14.05	13.51	14.91	12.20
24. CO-lb/h		7.37	7.89	9.86	8.37
25. O_2-lb/h		9.40	8.73	7.98	7.81
26. HC-lb/h		0.72	0.97	0.99	1.24
27. NO_x-lb/h		0.04	0.03	0.03	0.03
28. CO-lb/Mode		1.965	2.105	2.630	2.233
29. HC-lb/Mode		0.193	0.259	0.265	0.331
30. NO_x-lb/Mode		0.012	0.009	0.009	0.008

TABLE C-15. TOTAL EMISSIONS CHARACTERISTICS AVCO LYCOMING IO-360-A1B6D ENGINE--SEA LEVEL STANDARD DAY

Mode	CO lb/hr	CO lb/Mode	HC lb/hr	HC lb/Mode	NO_x lb/hr	NO_x lb/Mode	F/A	Max. CHT-°F
Taxi (16.0 - Min.)	10.0	2.667	0.550	0.1467	0	0	0.0950	
Takeoff (0.3 - Min.)	110.0	0.550	1.300	0.0065	0.350	0.00175	0.0950	440
Climb (5.0 - Min.)	80.0	6.667	0.900	0.0750	0.300	0.02500	0.0920	425
Approach (6.0 - Min.)	45.0	4.500	0.700	0.0700	0	0	0.0920	345
lb/Cycle		14.384		0.2982		0.02675		
lb/Cycle/RBHP		0.0719		0.00149		0.000134		
Federal Limit		0.0420		0.00190		0.00150		
Diff. = 6 - 7		+ .0299		- .00041		- .001366		
(8 + 7) x 100		71.2		-21.6		-91.1		
% of STD. = 9 + 100		171.2		78.4		8.9		

TABLE C-16. TOTAL EMISSIONS CHARACTERISTICS AVCO LYCOMING IO-360-A1B6D ENGINE--SEA LEVEL HOT DAY (T_I=95° F, INDUCTION AIR DENSITY = 0.0714 lb/ft^3)

Mode	CO lb/hr	CO lb/Mode	HC lb/hr	HC lb/Mode	NO_x lb/hr	NO_x lb/Mode	F/A	Max. CHT-°F
Taxi (16.0 - Min.)	10.0	2.667	2.000	0.5333	0	0	0.0940	
Takeoff (0.3 - Min.)	115.0	0.575	1.200	0.0060	0.150	0.00075	0.0970	440
Climb (5.0 - Min.)	85.0	7.083	0.975	0.0812	0.130	0.01083	0.0940	420
Approach (6.0 - Min.)	47.5	4.750	0.700	0.0700	0.050	0.00500	0.0940	355
lb/Cycle		15.075		0.6905		0.01658		
lb/Cycle/RBHP		0.0754		0.00345		0.000083		
Federal Limit		0.042		0.0019		0.0015		
Diff. = 6 - 7		0.0334		0.00155		- .00142		
(8 + 7) x 100		79.5		81.6		-94.5		
% of STD = 9 + 100		179.5		181.6		5.5		

TABLE C-17. ARITHEMATIC AVERAGING OF BASELINE DATA AVCO LYCOMING IO-360-A1B6D ENGINE

Baseline No.	CO lb/Cycle/RBHP	HC lb/Cycle/RBHP	NO_x lb.Cycle/RBHP	Avg. Cycle T_i-°F	Avg. Cycle F
1*	0.0697	0.00135	0.000225	72	0.0840
2**	0.0727	0.00239	0.000215	87	0.0934
3	0.0725	0.00132	0.000220	54	0.0920
4*	0.0660	0.00099	0.000260	69	0.0825
5*	0.0769	0.00161	0.000150	111	0.0890
6	0.0732	0.00202	0.000220	80	0.0902
Avg. Baseline	0.0718	0.00161	0.000215	79	0.0885
Federal Standard	0.0420	0.00190	0.00150		
Percent (%) of Standard (Applies to Emiss. Data Only)	171.0	84.7	14.3	79	0.0885

NOTES:

* Engine cleared prior to testing in the taxi-out mode

** This baseline test was preceeded by several takeoff, climb and approach mode lean-out tests